United States Maritime Administration
VESSEL OPERATOR
ENGINE EMISSIONS MEASUREMENT GUIDE

Final Report

Submitted by

James J. Corbett, P.E., Ph.D.
Principal Investigator
University of Delaware

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EXECUTIVE SUMMARY

Exhaust emissions monitoring has become an increasingly important issue as the marine transportation community seeks to reduce air emissions. However, estimates of current and projected pollution from marine engines are based largely on emissions calculations rather than onboard measurements. These calculations make standard assumptions about vessel operations, engine load profiles, and emissions characteristics in the same way that emissions estimates are calculated for other air pollution sources. While this approach has been proven effective for large-scale inventories of emissions from well-understood sources like factories and cars, these methods may be less accurate when applied to sources that have not been extensively studied. It is widely acknowledged that in-service engines perform differently than the new engines tested and certified by manufacturers. Moreover, individual engines may not perform like the "average engine" described using composite industry profiles or international standards.

The Maritime Administration (MARAD), in support of U.S. fleet technology development and modernization, has provided support for some of these tests and expects more operators will choose to test their marine engine emissions,. As the principal advocate within Government for U.S. maritime interests, MARAD has initiated a Maritime Energy and Clean Emissions Program. The Program seeks to:

- Investigate and demonstrate the potential for new technologies and fuels to improve marine power plant efficiency and to reduce air emissions.
- Provide guidance and information on maritime energy and emissions regulatory and policy issues.
- Protect the human and natural environment directly in contact with marine activity.

This document provides general guidelines and information to an operator who wants to monitor the emissions from one or more of the engines in a fleet of vessels. These guidelines are a result of a partnership between MARAD, the University of Delaware, and industry to research, develop, and disseminate information on energy and emissions technology and technology applications.

This report provides background discussion and outlines several reasons operators may choose to have their vessels tested. The include improving engine efficiency, meeting regulations, demonstrating environmental stewardship, and contributing to public knowledge and research. Fundamentals of emissions testing are presented, along with a summary of existing standard protocols.

The report is designed to help operators choose what to specify in an emissions test, and how to use the test analysis results. This includes identifying a clearinghouse concept that may be established by the Maritime Administration or other agency to assist the industry. Appendices are also provided with sample test reports and a marine emissions protocol.

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1 INTRODUCTION

Exhaust emissions monitoring has become an increasingly important issue as the marine transportation community seeks to reduce air emissions. Reasons for this increased attention are several. Nonroad engines are generally less regulated for air pollution than onroad vehicles, such as cars that have been regulated for more than 30 years. Nonroad emissions have been recognized as an important contributor to air quality problems in major metropolitan regions. Among nonroad sources, marine engines are the least regulated and fastest growing sources of air pollution. Because of increased trade and transportation by ships and ferries, many regions project that marine vessel emissions will double over the next decade without increased emissions control.

However, estimates of current and projected pollution from marine engines are based largely on emissions calculations rather than onboard measurements. These calculations make standard assumptions about vessel operations, engine load profiles, and emissions characteristics in the same way that emissions estimates are calculated for other air pollution sources. While this approach has been proven effective for large-scale inventories of emissions from well-understood sources like factories and cars, these methods may be less accurate when applied to sources that have not been extensively studied. It is widely acknowledged that in-service engines perform differently than the new engines tested and certified by manufacturers. Moreover, individual engines may not perform like the "average engine" described using composite industry profiles or international standards.

Some operators of marine vessels have commissioned emissions testing for select vessels to determine if their engines perform similarly to the calculated estimates. The Maritime Administration (MARAD), in support of U.S. fleet technology development and modernization, has provided support for some of these tests and expects more operators will choose to test their marine engine emissions,. As the principal advocate within Government for U.S. maritime interests, MARAD has initiated a Maritime Energy and Clean Emissions Program. The Program seeks to:

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This document provides general guidelines and information to an operator who wants to monitor the emissions from one or more of the engines in a fleet of vessels. These guidelines are a result of a partnership between MARAD, the University of Delaware, and industry to research, develop, and disseminate information on energy and emissions technology and technology applications.

These guidelines for emissions monitoring for in-service marine engines will assist operators and marine policy makers in obtaining and reporting consistent emissions data for marine engines. These guidelines will enable operators to successfully measure and report emissions from uncontrolled and controlled engine systems in a manner that will allow meaningful comparisons between alternative power systems and emission control technologies. Over time, marine engine tests that are properly and consistently reported will provide greater understanding of this source of air pollution. Like factories and cars, this improved understanding based on adequate test data will increase the accuracy of emissions factors and load profiles and make inventory estimates more representative of actual fleet emissions.

1.1 Recent Policies Focus on Marine Vessel Emissions

Emission testing can be timely and useful for vessel operators, given recent policy development internationally and domestically. In 1997, the International Maritime Organization (IMO) adopted a Protocol to amend MARPOL 73/78 (IMO 1998), adding a new Annex VI to the Convention entitled "*Regulations for the Prevention of Air Pollution from Ships*." When it comes into force, MARPOL Annex VI will set limits on sulfur oxide and nitrogen oxide (NOx) emissions from ship exhausts and prohibit deliberate emissions of ozone depleting substances. In addition, IMO has begun discussions on climate change gases, including carbon dioxide (CO_2), with the aim of developing technical measures to reduce their emissions. Six of 15 required Flag States, accounting for about 25% of the required 50% gross tonnage of the world's merchant shipping, have ratified Annex VI as of 3 September 2002.[1]

The U.S. Environmental Protection Agency (EPA) established engine emission controls for U.S.-flag commercial marine vessels operating domestically, and recently proposed regulations for large engines on oceangoing U.S. vessels (EPA 1999; EPA 2002). State and local governmental organizations charged with designing and implementing emission control programs have mounted significant efforts in recent years to improve air quality by reducing ozone concentrations and other pollution. EPA-mandated state implementation plans, combined with federal mobile source emission control programs, have been very successful for other non-marine sources of air pollution. The main precursors of ozone, NOx and volatile organic compounds (discussed in Section 2), have been reduced in many areas, and average ozone levels are beginning to decrease.

However, current regional inventories place increasing importance on marine vessel emissions, especially NOx, particulate matter (PM), and oxides of sulfur (SOx). EPA forecasts that increased transportation and trade associated with economic growth will cause emissions to increase and eventually outpace per-source reductions in air pollution. In San Francisco Bay and in Los Angeles County ship exhaust emissions account for more than 4% of current NOx inventories; projections for these regions suggest that emissions from marine vessels will double over the next decades, through trade growth and/or ferry expansion unless pollution controls are adopted. States like California and Texas are including emissions reduction goals for marine vessels in their state implementation plans to meet air quality goals under federal Clean Air Act requirements (California Air Resources Board 1994; TNRCC 1999).

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[1] The United States recently announced that the President will submit Annex VI for ratification by the U.S. legislature (source: http://www.state.gov/r/pa/prs/ps/2002/10039.htm). This would add one nation and about 3% of gross tonnage toward the requirements for "entry into force."

Even local government agencies like the (San Francisco) Bay Area Air Quality Management District, the South (California) Coast Air Quality Management District, and the Ports of Los Angeles and Long Beach are attempting to quantify and reduce emissions from marine engines. A memorandum of agreement between multiple local and state agencies has established a voluntary speed reduction zone within 20 miles of the Ports of Los Angeles and Long Beach in San Pedro Bay (Los Angeles Board of Harbor Commissioners, Yamaki et al. 2001). This agreement attempts to reduce NOx emissions (primarily) by requesting all vessels to transit this region at 12 knots. This agreement, like other federal and international policies, is based on calculated benefits of speed reduction but would require emissions testing to verify the actual reductions.

2 BACKGROUND

Marine engines power ferry vessels, fishing vessels, workboats, pushboats, towboats, and cargo vessels of all types. Whether the vessel is a high-speed passenger ferry, a towboat pushing a string of loaded barges, or a modern container ship meeting scheduled liner service, most marine engines have important similarities. Nearly all marine engines are compression-ignition engines (operating on the Diesel cycle); by contrast most automobile engines are spark-ignited (operating on the Otto cycle). Marine engines are designed for a combination of power and fuel economy that makes them efficient prime movers for propellers and on-board electric power generation. The rugged design and reliability of marine engines have been proven under emergency conditions and in the harshest of ocean and coastal environments. Marine engines are capable of using a wide variety of auto-igniting fuels, including traditional diesel fuel, other distillate fuels, biofuels, gaseous fuels, and heavy residual fuels. Because of its low cost, marine engine manufacturers developed technology to accommodate residual fuel in large low-speed diesel engines; however, these fuels contain higher levels of contaminants (e.g., sulfur, metals, ash) than higher-cost distillate fuels. Marine engines, along with engines on other non-road equipment, are also the least environmentally controlled mobile sources of air pollution.

Marine vessel operators are generally concerned about operating their ships responsibly and have made important improvements in vessel safety to avoid the risks of accidental spills, releases, and collisions that may affect marine ecosystems. Ship environmental concerns have mostly been focused on impacts to water, coastlines, or the abundant species in our ports, harbors, and shipping lanes. As scientific understanding and environmental policy has become more aware of air pollution impacts from non-road sources, marine vessel operators want to ensure that their activities are consistent with good environmental stewardship, and minimize risk to public health. Of course, vessel operators need to know how much of an impact the reduction of ship engine emissions may have in order to evaluate the alternatives to reduce engine pollution. Testing the engines onboard existing vessels can be one of the most direct ways to evaluate current engine exhaust characteristics and to determine the positive results of reduction technologies or operational improvements.

This section provides background discussion on the formation of engine emissions, including harmful effects of exhaust pollutants. Much of this discussion does not apply exclusively to marine engines; air pollution is a result of nearly every modern combustion process. The purpose of this discussion is to provide marine vessel operators with a working understanding of the air pollution and air quality concerns that have motivated recent attention on marine engine emissions. This understanding is useful for those fleet managers and operators who may be motivated to commission emissions testing for one or more of the marine engines on their vessels.

2.1 Diesel Emissions Characteristics

Like any combustion system, marine engines burn a fuel to release heat and produce power. The process of releasing this energy involves the oxidation of hydrocarbons to produce primarily water and carbon dioxide. However, the fuel and air used in combustion typically contain more elements than hydrogen and carbon and oxygen. Entering the marine engine in one stable molecular arrangement, these additional elements form new molecules during chemical reactions under the intense heat and pressure of engine combustion. In general, these unnecessary products of combustion – these reactions do not typically release useful energy – include the pollutants that affect our health and environment. The next paragraphs provide an overview of the most important of these emissions.[2]

Diesel engines without emissions control emit high concentrations of oxides of nitrogen and particles, and low concentrations of carbon monoxide and hydrocarbons (Health Effects Institutes, Diesel Epidemiology Working Group et al. 2002). These are characteristics of thermally-efficient, high-temperature, high-pressure, heterogeneous combustion that make diesel engines the most common prime mover in marine service. Because diesel engines are more efficient combustion systems than other types of combustion (e.g., gasoline engines), they emit less carbon dioxide per unit of work. Moreover, if the fuel burned in diesel engines has significant levels of sulfur and other contaminants, high emissions of oxides of sulfur and other pollutants may also be produced; this is the case in many marine diesel engines that are designed to use less expensive distillate or residual fuels.

Carbon Dioxide (CO_2)
Carbon dioxide and water account for the largest fraction of exhaust gas flow from diesel engines. While neither is considered a pollutant in the traditional sense (i.e., CO_2 and water do not contribute to air quality problems like smog), carbon dioxide is a greenhouse gas. Carbon dioxide can remain stable in the atmosphere for many decades, as long as 50-100 years or more. It acts to trap the sun's energy and reflected energy from the earth's surface, which contributes to warming of the atmosphere. Because all of the carbon is provided by hydrocarbons in the fuel (except for small amounts of lube oil consumption), CO_2 emissions are directly proportional to fuel consumption. This means that if we assume complete combustion, the same number of carbon atoms leave the engine as CO_2 as enter it in the fuel.

One question that is often asked is why does the amount of CO_2 emitted exceed the amount of fuel consumed? The short answer is the weight of fuel plus the weight of oxygen in air that forms CO_2 adds up to more than the weight of fuel alone. A more complete answer requires recalling a bit of high-school chemistry. The fuel only provides the carbon (one carbon and two oxygen atoms make up CO_2). Fuel is about 86% carbon by weight, so take the weight of fuel

[2] Some of this information is taken from the U.S. EPA website for the Office of Transportation and Air Quality. For further information, see http://www.epa.gov/otaq/invntory/overview/pollutants.

and multiply by 0.86 to get the weight of carbon emitted. That number is smaller than the fuel amount. But where is the O_2 in CO_2? The oxygen comes from the air. The molecular weight of Carbon is 12 and the molecular weight of Oxygen is 16. If we add that up, we get a molecular weight of 44 (= 12 + 16 + 16) – which is 3.67 (44/12) times greater than the carbon alone.

There are essentially three ways to reduce carbon dioxide emissions:

a) Improve fuel economy: Reducing the amount of fuel burned will reduce carbon emissions. This also reduces operating costs, so many marine vessel operators choose engine designs that minimize fuel consumption for a given service. However, some vessels (especially ferries) are designed for speed or other performance characteristics, where fuel costs are not the prime determinant of hull design or engine selection.
b) Switch fuels: If an engine can burn a fuel that has significantly less carbon than liquid petroleum fuels (less than ~86% carbon), but provides similar energy, then carbon dioxide emissions will be reduced. Alternative fuels have been an important focus of energy research (DOE 1995), and they have potential applications in the marine industry (Farrell, Keith et al. in press). The marine industry has been innovative by accommodating less expensive fuels (heavy residual fuels) that most diesel engine users find to be unacceptable. However, the lower-carbon alternative fuels are usually more expensive than current alternatives and have been resisted by industry.
c) Remove CO_2 from the exhaust stream: This is the technique used for many other pollutants, like NOx, but it less practical for CO_2. If we can prevent the carbon from exhaust gases from being released to the environment, then it cannot function as a greenhouse gas. Current research includes efforts to remove carbon (either as CO_2 or in some other stable form) from the exhaust stream and store it underground or in deep ocean pockets (Keith 2000; Keith and Parson 2000). These techniques are not practical yet on large scales, and will likely work for stationary combustion systems before being applied to mobile sources such as ships.

Oxides of Nitrogen (NOx)

Only about 21% of atmospheric air is oxygen, the gas needed for combustion; the majority of atmospheric air is nitrogen gas. Under the high pressure and temperature conditions in an engine, nitrogen and oxygen atoms in the air react to form nitrogen oxide and nitrogen dioxide, collectively known as NOx. In some marine fuels (particularly residual fuel) some nitrogen may be bound in the fuel; the fuel-bound nitrogen will also oxidize during combustion. While fuel-based NOx must be considered if present, most of the NOx formed in marine engines uses available nitrogen provided by combustion air. Large, low-speed diesels make efficient use of low-grade residual fuel because of their high compression (high heat) characteristics. That high heat, sustained in relatively long combustion chamber process, is a prime contributor to NOx formation. As such, their contribution to the NOx problem is a direct byproduct of their fuel efficiency.

Mobile sources are responsible for more than half of all nitrogen oxide emissions in the United States (EPA 1998). In general, NOx is a regional pollutant that can travel long distances, causing a variety of health and environmental problems in locations far from their emissions source. These problems include ozone and smog, which are created in the atmosphere from nitrogen oxides, hydrocarbons, and sunlight. On smoggy days, this pollution can affect human respiratory systems. NOx also contributes to regional haze, making it difficult to see distant objects. Nitrogen oxide emissions also contribute to the formation of particulate matter through chemical reactions in the atmosphere. This is called “secondary particulate matter” since the particles are formed after exhaust gases are released into the atmosphere. These particles contribute to the formation of acid rain.

Particulate Matter (PM)

Particulate matter is the term for solid or liquid particles found in the air. Some particles are large or dark enough to be seen as soot or heavy smoke, but fine particulate matter is not visible to the naked eye; however, fine particles absorb and scatter light so that a cloud or plume of these particles may be visible. There is a tendency to focus on PM in diesel exhaust because it is often a visible component, but diesel exhaust includes much more than the visible PM. Mobile source particulate emissions consist mainly of these very tiny particles, also known as PM2.5, because they are less than 2.5 microns in diameter. According to the EPA, diesel-powered mobile sources contribute more than half of the mobile source particulate emissions (EPA 1999).

Diesel engine particulate matter is an increasing concern for air pollution because of two basic reasons. First, “state, national, and international agencies have concluded that diesel exhaust is a probable lung carcinogen” (Health Effects Institutes, Diesel Epidemiology Working Group et al. 2002). This conclusion has important public health consequences for port, coastal, and inland river areas where marine diesel engines and other diesel vehicles (e.g., freight trucks and rail) are prevalent. Second, policy makers are interested in diesel engine emissions because we do not know which of its properties are most important to control so that health effects are reduced. Because of this, many public agencies are testing sources for PM to learn more.

A brief summary of known PM properties is quoted below from a recent Health Effects Institute report outlining needed research to better understand human exposure and health risks (Health Effects Institutes, Diesel Epidemiology Working Group et al. 2002):

> “Diesel particles are complex, covering a range of sizes and [formation properties], and having myriad chemical components that vary with engine characteristics, operations, and fuels. Because of this complexity, the physical and chemical characteristics of diesel particles have not been fully [understood] and only a relatively small fraction of the mass of organic emissions has been identified by chemical species.
>
> “The size distribution of exhaust particles is relevant to potential health risks, as size is one of the key determinants of penetration into the lung and the site of deposition in the lung. The size distribution of diesel particles differs from engine to engine, among fuels, and with operating conditions in the same engine, such as engine load and exhaust dilution. Like most combustion-generated aerosols, diesel particles are relatively fine; the typical particle has a small aerodynamic diameter, less than 1 micro meter (1 μm). … Particles of this size are nonspherical, consisting of much smaller particles that have agglomerated. They may contain condensed material such as [semi-volatile organic compounds (SVOCs)] and sulfuric acid. …
>
> “Chemically, diesel particles are composed primarily of [elemental carbon (EC)], [organic carbon (OC)], and sulfate, although their composition is highly variable. For example, the EC component can range from about 30% to 90% of the mass. In general, about 30% of the mass is composed of [OC material, including] unburned oil and fuel and partially combusted or pyrolysis products, with the remainder as condensed inorganic oxides (eg, sulfate), water, and ash, which can contain trace metals.”

Fine particulate matter is a health concern because very fine particles can reach the deepest regions of the lungs (EPA 1998) (Health Effects Institutes, Diesel Epidemiology Working Group et al. 2002). Health effects include asthma, difficult or painful breathing, and chronic bronchitis, especially in children and the elderly. Fine particulate matter associated with diesel exhaust is also thought to cause lung cancer and is therefore listed as a mobile source air toxic. Fine particulate matter can travel long distances on air currents and is also a major cause of haze, which reduces visibility, affecting cities and scenic areas throughout the United States.

Hydrocarbons (HC)

Similar to particulate matter characteristics, the composition of unburned and partially oxidized hydrocarbons in diesel exhaust is much more complex than it is for spark-ignited engines (Heywood 1988). This is primarily because diesel fuel contains fuel molecules that have higher boiling points and higher molecular weights than gasoline. Those hydrocarbons that condense to particles are counted as PM. Species of HC, from methane to heavier hydrocarbons, that remain in the vapor phase at exhaust temperatures are termed hydrocarbons.

Hydrocarbon emissions from marine diesel engines can very widely with operating conditions, and different forms of hydrocarbon molecules form at different operating modes (Heywood 1988). At full load, marine diesel engines produce very low HC emissions; during idle or light-load periods, HC emissions are much higher. Lots of factors affect HC emissions, including running the engine too lean or too rich, and variable cylinder wall temperatures typically associated with load changes. Hydrocarbons react in the presence of nitrogen oxides and sunlight to form ground-level ozone, a major component of smog. A number of exhaust hydrocarbons are also toxic, with the potential to cause cancer.

Carbon Monoxide (CO)

Carbon monoxide (CO) is another mobile source pollutant, along with NOx, HC, and PM, although properly maintained diesel engines emit very little CO compared to spark-ignited engines. CO causes adverse effects on human health, including toxic effects on blood and tissues, and effects on organ functions. CO has been linked to fetal brain damage, reduced visual perception, cognitive functions and aerobic capacity, and increased risk of heart problems for people with heart disease. EPA reports that approximately 20 serious or moderate CO non-attainment areas exist in the United States (EPA 1998).

Other Pollutants

Diesel engines also emit other pollutants, some of which are dependent upon fuel properties. These include sulfur dioxide (mentioned above), carbonyls, toxic air contaminant such as benzene, and trace metals. These are not yet the focus of most marine vessel testing and are not addressed further in these guidelines, but may be included in some testing protocols.

2.2 Basic Terms and Definitions of Emissions Testing

There are a set of terms and definitions that most emissions test protocols use. These terms and definitions will be used in this document, to describe specifications for requesting an emissions test and to discuss ways to interpret results.

Engine family: Manufacturer's grouping of series-produced engines that are expected to have similar exhaust emission characteristics, and are used as produced, requiring no adjustments or modifications which could adversely affect their NOx emissions (ISO 1996; IMO 1998).

Engine group: Smaller series of engines produced for similar applications, requiring minor adjustments and modifications during installation or in service on board. These are normally large main propulsion engines of the same type and design features (IMO 1998).

Major conversion: Modification of an engine where the engine is replaced by a new engine, a substantial modification is made to the original engine configuration, or the maximum continuous rating is increased by more than 10% (IMO 1998).

Mode: An engine operating point of speed and power (or torque) (ISO 1996; IMO 1998).

Mode length: The time between leaving the speed and/or torque of the previous mode (including time to change speed/power/torque and the stabilization at the beginning of each mode) and the beginning of the following mode (ISO 1996).

Particulates: Exhaust material, primarily carbon, condensed hydrocarbons, and sulfates and associated water, collected on a filter after diluting diesel exhaust with clean filtered air to a temperature ≤52° C (ISO 1996).

Preconditioning of the engine: Warming up of the engine at the rated power used in the test cycle to stabilize the engine parameters according to the recommendations of the manufacturer (ISO 1996).

Rated speed: Speed at which the rated power is delivered by the engine (ISO 1996).

Specific emission: Mass flow rate of pollutants (grams per kilowatt-hour), preferably based on brake horsepower (ISO 1996). In marine applications, specific emissions are also commonly reported in fuel-based terms (kilograms per tonne fuel).

Test cycle: A sequence of engine test modes each with a defined speed, power (or torque), and weighting factor (ISO 1996; IMO 1998). The following example is for constant speed main propulsion application, including diesel-electric drive and variable-pitch propeller installations:

ISO E2 test cycle	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	Weighting factor	0.2	0.5	.015	.015

3 MOTIVATION OF EMISSIONS TESTING

In specifying the details of an emissions test, an operator can apply this background information so that they include those analyses that meet their particular needs or address the requirements of a public agency. This background information may also assist operators in sharing their information with MARAD or other organizations to improve the body of research and understanding related to in-service marine engines. However, background information on emissions does not directly address the potential reasons that vessel operators may want to test marine engines in their fleets.

There are at least four main reasons why operators are increasingly interested in measuring the emissions from marine engines, discussed below. These reasons include:

- Improving engine performance and efficiency,
- Meeting regulations (mandatory or voluntary),
- Demonstrating environmental stewardship, and
- Increasing public knowledge.

3.1 Test to Improve Engine Efficiency

Port Engineers know that good preventive maintenance and proper operation reduce unscheduled repair costs and increase fuel efficiency and/or performance. Similar to the increased use of diagnostic equipment in automobiles and trucks, marine engines are modernizing to take advantage of electronic controls and advanced diagnostics. By making proper adjustments to the engine, an operator may improve fuel economy and improve plant efficiency. Emissions testing can be a useful tool in this regard, because it enables a finer tuning of engine performance.

Emissions testing can also confirm whether new equipment installed during an engine overhaul period achieves the intended performance after the vessel in back in service. Testing of current fleet emission characteristics can also provide information about the best- and worst-emitting vessels in a fleet that may assist operators in fleet modernization planning.

3.2 Test to Meet Regulations

Engine manufacturers certify that new engines meet all regulations and performance standards at the time of sale. An engine’s efficiency and performance may degrade over time, depending on the quality of routine and preventative maintenance, operating adjustments, and engine wear. For on-road mobile sources (e.g., cars and trucks), periodic smog checks test emissions under standard operating settings to determine if these engines still comply. While current regulations do not require that in-service marine engines be tested, engine testing may be a requirement if the engine receives a major conversion (defined above). However, engine testing is one of the alternatives by which operators can verify their engines meet standards. Moreover, some regulations and voluntary retrofit programs may require one-time emissions testing and/or periodic monitoring. Regulations that include in-use testing exist at the international, federal, state and local levels. The following paragraphs summarize these requirements.

3.2.1 International Requirements

The International Maritime Organization recognizes that NOx from ships impacts the environment, and has adopted NOx emissions standards under MARPOL Annex VI. IMO also prepared one of the standard protocols for monitoring these emissions (IMO 1998; Skjølsvik, Andersen et al. 2000). (The IMO protocol will be discussed in Chapter 5 of this report.) These regulations may require operators of older vessels to conduct emissions testing as part of the Supplement to International Air Pollution Prevention Certificate, if the engines are modified to extend their useful life, adapt the vessel performance for new service, or for other purposes.

3.2.2 Federal Requirements

The U.S. EPA established emissions standards for new marine diesel engines (EPA 1999; EPA 2002), and set forth guidelines for emissions monitoring. EPA regulations specify that onboard emission testing may be used to "identify and hold manufacturers responsible for noncompliance with the emission standards (including the Not-to-Exceed limits). The Clean Air Act authorizes [EPA] to pursue an emission-related recall if … a substantial number of engines, when properly maintained and used, do not conform to the regulations throughout their useful life" (EPA 1999). EPA also expects operators who participate in the voluntary low-emitting engine program (known as the Blue Sky program) may use emission testing to demonstrate compliance with the voluntary emissions standards.

Other nations, such as Sweden and Norway, have designed voluntary programs that require demonstration of compliance. Operators participating in these programs may also choose to test their engines to meet program requirements. Since this document is focused on vessel operations in U.S. waters, it does not include details on these programs.

3.2.3 State and Local Requirements

Several states and local agencies are pursuing emissions testing as way to increase the quality of data used in estimating total emissions from vessels operating in certain regions. For example, the Port of Los Angeles announced a Clean Air Plan in October 2002 that will support ship emissions research and efforts to retrofit vessels (e.g., demonstration projects) (Port of Los Angeles 2002). Similar activities have involved ferry vessel testing, tug-boat testing, and large vessel testing in ports such as Houston, New York/New Jersey, Norfolk, San Francisco and San Diego. Many state and local organizations are also considering incentive programs or providing funds for demonstration projects; participation in these activities usually requires emissions testing by an operator.

3.3 Demonstrate Environmental Stewardship

Emissions testing can also meet local goals. For example, ferry expansion plans to improve regional mobility have used emissions testing to quantify the current fleet performance and to suggest how much new technology can reduce emissions in an expanded fleet (URS Corporation). Emissions tests are also commissioned by public and private groups to address environmental concerns of stakeholders. The Water Transit Authority in San Francisco California used emissions testing to show that three in-service ferries produced emissions significantly lower than manufacturer ratings (Water Transit Authority 2002). Results of vessel testing can be shared with interested stakeholders (e.g., environmental interest groups), and may help demonstrate willingness of operators to pursue best practices to reduce environmental impact.

3.4 Increase Public Knowledge

Emission testing results, when properly reported and published, add to cumulative data on fleet profiles. Some emissions tests are only summarized publicly, and do not find their way into peer-reviewed literature (articles and conferences). These are of limited use, unless the full test protocol and complete results are released. Other emissions tests are made available to public agencies, such as MARAD/DOT, state environmental officials, or directly to ports and local officials. These test results can be very valuable, but they may not be catalogued well for later use, diminishing their value to policy makers and researchers. Even if the existence of the testing is known, results may not be obtained easily after a few months. In this case, a clearinghouse where emissions reports are catalogued may be helpful.

Peer-reviewed or widely available public reports of emissions testing are most valuable. These test reports can be evaluated along with previous studies to improve general understanding of engine emissions trends and patterns. Moreover, complete test data continue to be useful, as later testing can be compared to show increased statistical significance and to quantify the effects of innovation in technologies. This report provides guidelines for emissions testing and reporting that will enable MARAD and other agencies to increase public knowledge through comparable formats and protocols.

4 FUNDAMENTALS OF EMISSION TESTING

Air and fuel are combined within the diesel engine cylinders at high temperatures and pressures so that they will mix and auto-ignite. During combustion, oxidation occurs to release energy (power and heat). This process includes chemical reactions that form exhaust gases. Exhaust gases are a mixture of the chemical products of combustion and materials (gases and solids) that flowed through the cylinder without reacting to form new products of combustion.

The fundamentals of emissions testing may be described using the schematic in Figure 4-1. At its simplest, an emissions test attempts to quantify the concentration of certain molecules that are present in the exhaust gas. These molecules are either the products of combustion reactions or chemical species that were passed through the engine without reacting.

As an example, consider oxygen, which is needed to oxidize fuel during combustion. Figure 4-1 shows that oxygen enters the engine with the intake air and oxygen is also present in exhaust gases. Some of the oxygen leaves the engine as part of molecules of carbon dioxide, water, or other oxides. Molecular oxygen in exhaust gas is part of the "excess air" that helps mix the combustion gases in the cylinder and force exhaust gas out of the engine.

Some emissions exhaust products are routinely measured as part of normal engine maintenance. Tuning an engine adjusts excess-air levels so they are not too large or too small and may be confirmed by measuring the oxygen in exhaust gas; this helps ensure proper combustion and improves fuel economy. These maintenance actions also prevent engine damage caused by poor timing of auto-ignition, etc. Similar to engine tests that measure normal products of combustion, like carbon dioxide and water, exhaust gas can be tested for the presence of a combustion pollutant (e.g., oxides of nitrogen or NOx).

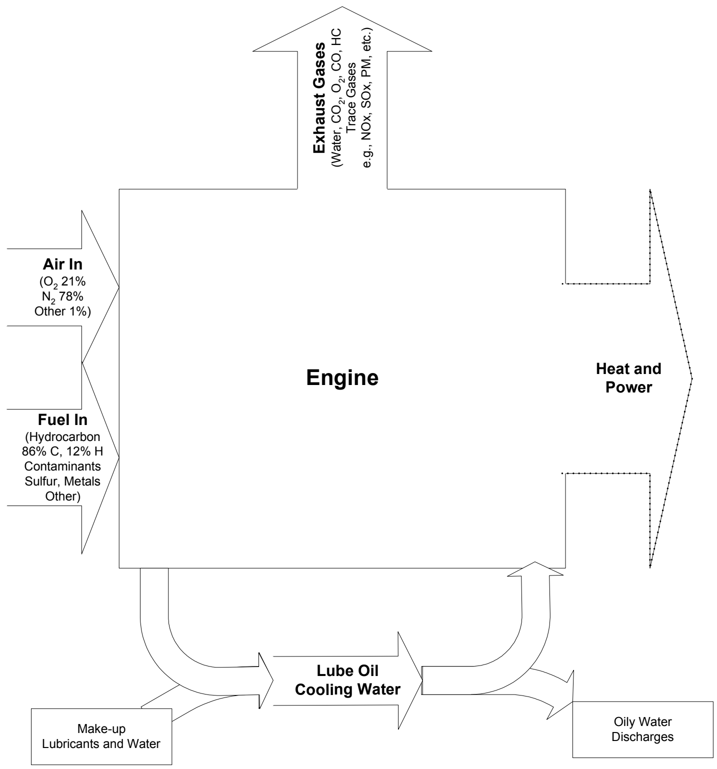

Figure 4-1. Simplified Schematic of Engine Inputs and Outputs

However, emission testing involves more than simply measuring the exhaust constituents. In order to understand how polluting an engine might be, one needs to understand how much pollution is produced for the amount of energy input or work output. By measuring pollution from combustion this way, we can tell if two different engines with similar exhaust concentrations of an important pollutant are in fact equally polluting.

A simplified example may be helpful. Consider two diesel engines that both are measured to produce NOx concentrations of 1400 parts per million by volume (ppmv) in raw exhaust gases.[3] One may be a very large, naturally-aspirated engine operating at half load; this means that each power stroke may have relatively less fuel and more excess air than when this engine operates at full load. In other words, we would expect the NOx concentrations measured under these conditions to be lower than when this engine operates at full-load temperatures and pressures. The second engine may be smaller, operating at full load. In the second case, the measured NOx concentrations might be more representative of the maximum rate at which that engine can produce NOx pollution.

[3] A parallel example could be constructed using diluted measurements from a constant volume sampler.

So in addition to measuring the pollutant concentration in exhaust gas (or diluted constant-volume sample), test procedures require that engine-operating conditions also be measured. This includes some means to quantify the total quantity of exhaust gas produced. Emissions test analyses convert these exhaust-gas relationships into the amount of pollution produced per energy input (fuel flow) and/or energy output (power or work) under each test condition. Typically, an engine is tested repeatedly under several expected throttle settings or engine load points that together describe the engine duty cycle. These tests can be summarized by a composite emissions factor based either on fuel flow or power output.

4.1 The General Combustion Equation

In an ideal combustion system, we would put into an engine only those materials necessary for the oxidation of fuel to release energy. The minimum quantity of oxidizer necessary to completely burn a quantity of fuel is called the stoichiometric quantity (Turns 1996). "If more than a stoichiometric quantity of oxidizer is supplied, the mixture is said to be fuel-lean, or just lean; while supplying less than the stoichiometric oxidizer results in a fuel-rich, or rich mixture" (Turns 1996).

The general equation for combustion is simplified below.

$$\begin{aligned}\text{Fuel}_{(\text{hydrocarbon}+\text{sulfur}+\text{contaminants})} + \text{Air}_{(\text{oxygen}+\text{nitrogen})} \rightarrow \text{Carbon products}_{(\text{CO}_2+CO+HC)} + \text{Excess Oxygen} + \text{Water} \\ + \text{Nitrogen products}_{(N_2+NO+NO_2)} + SO_2 + \text{Other products}\end{aligned}$$

In spark-ignited (e.g. gasoline) engines, the air-fuel mixture may often be rich; this is part of the reason why automobile engines have higher emissions of hydrocarbons, or unburned fuel. In compression-ignited (e.g. diesel) engines, the air-fuel mixture is almost always lean, except under rapid changes in load; this makes diesel engines very good at achieving complete combustion, with very low carbon monoxide and hydrocarbon emissions. During startup periods, many engines experience rich conditions; engines that produce smoke are often emitting unburned or incompletely burned fuel particles.

Depending on engine design and operating conditions, the relative amounts of each of the combustion products will vary. For example, reducing sulfur in the fuel will directly reduce the oxides of sulfur (primarily SO_2) contained in exhaust gases. About 4% to 10% of the exhaust gases may be carbon species (Heywood 1988). In typical compression-ignition engines, combustion of fuel is complete; this means that CO_2 accounts for most of the carbon products and that very few fuel molecules of partially oxidized carbon (CO) and unburned hydrocarbons (HC) are formed. Excess air is used to ensure complete combustion and (especially in two-stroke engines) to assist in removal of combustion products from the cylinder before the next power stroke; typically excess oxygen levels can be between 6% and 14% depending on load conditions (Heywood 1988).

Products of combustion that are considered pollutants, such as NO and NO_2, SO_2, etc., are often considered negligible in balancing the combustion equation above. However, that fact should not be confused with their potential to negatively affect the environment. For example, consider a high-speed marine diesel engine with a displacement of 65 liters per revolution. NOx (NO and

NO_2) may form in the exhaust gases of a marine engine at very low concentrations measured in parts per million (e.g. 1400 ppmv or 0.14% by volume) relative to other gases. However, depending on fuel usage, these emissions can result in significant releases of pollution per day. For example, this engine consuming just two tons of fuel per day might emit (more than 140 kilograms NOx per day). Total pollution released to the environment is a function of the combustion products formed and the total quantity of exhaust gas produced over a given time.

4.2 Exhaust Flow Rates and/or Fuel Flow Rates

In an emissions test, some measure of the total mass of material involved in combustion must be obtained. This can be done three different ways: 1) directly by measuring exhaust-gas flow-rates; 2) directly using a partial- or full-dilution constant volume sampling system; 3) indirectly by measuring fuel flow-rates; and/or 4) indirectly by measuring intake-air flow-rates.

Directly measuring exhaust gas flow appears simple, but this can be a difficult task. Exhaust gas velocities are not uniform across the diameter of the stack and mass flow rates vary with gas density (a variable function of temperature and pressure). Precautions must be taken to avoid measurement errors (ISO 1996).

A constant-volume sampling system (referred to as a dilution method) may be useful in measuring transient emissions because it measures total mass flow of exhaust over a cycle of operation (Weaver and Balam-Almanza 2001). In a CVS system the pollutant concentration in the dilution tunnel is proportional to the pollutant mass flow rate in the exhaust. Pollutant concentrations in dilute exhaust may be easier to measure, while raw exhaust mass flow rates are difficult and expensive to measure accurately, especially under transient conditions. However, rather than measuring the direct transient emission rates in raw exhaust, the dilution sampler obtains a measure of the total pollutant mass emissions over a given driving cycle. Technically, this is equal to the integral of pollutant mass flow rate over that cycle, and can produce very accurate results. This is the kind of sampling system best suited for PM measurements and can achieve quality measures of gaseous emissions as well.

Indirect measurement of exhaust gas flow requires measuring the air-flow and/or fuel-flow rates. If the air and fuel flow rates are directly measured with sufficient accuracy, the sum of these mass flow rates should equal the exhaust flow rate in a properly functioning engine. (Lube oil consumption is negligible to total exhaust mass flow.) Measuring both air- and fuel-flow rates is generally easier than direct measurement of exhaust flow rates. However, not all engines are equipped to provide both of these measures, and precautions are still needed to ensure that these measurements accurately represent exhaust flow.

The general combustion equation can be used to balance measured concentrations of exhaust-gas species with either the fuel- or air-flow rates. The preferred method in standard protocols is to use fuel consumption measurements and a "carbon balance" that solves the general combustion equation for mass flow of exhaust gas required to account for all of the carbon in the fuel. This is partly because carbon species are more often measured as part of normal engine monitoring. Most engine control instruments and data loggers monitor excess air, carbon dioxide, and carbon monoxide in exhaust gas to inform the ship's engine crew.

The carbon balance uses the combustion equation to require that the mass of the mixture of carbon molecules that goes into the engine equals the mass of carbon molecules in the exhaust. Protocols typically follow the carbon balance, assuming knowledge of the fuel consumption (ISO 1996). One carbon balance method is simpler, but only valid for fuels without oxygen and nitrogen content. A "universal, carbon/oxygen balance" method can be used when the fuel consumption is measured and fuel composition is known. The universal method is applicable for fuels containing hydrogen, carbon, sulfur, oxygen, and nitrogen in known proportions. Similarly, an "oxygen balance" or "hydrogen balance" can be used to solve for the mass flow of exhaust gas required to account for all of the oxygen in the intake air.

In all approaches, the measurements of actual air, fuel, and exhaust flows must consider the amount of humidity in the exhaust air. Water (vapor) is one of the primary products of combustion and would account for significant mass flow. Standard reporting requires that all measurements be converted into equivalent values for dry exhaust or reported for a standard "wet" exhaust. Without specifying these conditions, test results cannot be usefully compared.

In sampling for particulate matter, there are ways to dilute the gases in the exhaust stack so that particle formation occurs in the test similarly to the way particles form as exhaust gas is released to the cooler atmospheric air. This is not discussed in detail in this guidance document because of the complexity and recent improvements in measurement technologies for PM measurements. Moreover, dilution equipment is typically large and cumbersome for use in shipboard monitoring – although more compact technology is emerging. Existing protocols address ways to provide partial- or full-flow dilution to ensure accurate and representative measurements (ISO 1996), but may be updated by new research. Following the latest methods is important because "the size distribution of diesel particles differs from engine to engine, among fuels, and with operating conditions in the same engine, such as engine load and exhaust dilution" (Health Effects Institutes, Diesel Epidemiology Working Group et al. 2002).

4.3 General Test Methods and Procedures

An emission test measures certain properties of exhaust gases and engine operation under defined conditions. Some properties are specified by protocol, such as fuel type and engine load, while other properties, such as exhaust temperature and exhaust species concentration, are dependent on the particular engine performance. All test methods define required accuracy for equipment that measures properties during the test, such as pollutant concentration or temperature, mostly following the International Organization for Standardization (ISO) standards (ISO 1996).

4.3.1 Instrument Performance Requirements

The required accuracy of instruments will vary with the type of parameter being measured. Some or all of the following engine related parameters are typically measured: engine speed, torque, power, fuel consumption, specific fuel consumption, air consumption, and exhaust gas flow. Temperatures, pressures, and humidity are also essential measurements that must meet deviation accuracy. Engine control monitors in typical ship's engine rooms may measure some parameters, such as coolant temperature, lubricating oil temperature, exhaust gas pressure and temperature, and inlet manifold pressures and temperature; however, these parameters may need to be measured independently if the engine log does not provide adequate sampling frequency or accuracy. Other parameters often are measured only during testing, such as intake air humidity, and the exhaust pressure, the temperature, and the flow rate in particulate matter dilution tunnels. For a specific list of measurement accuracies, refer to the relevant protocols (discussed in Section 5).

Gaseous emissions are sampled with one or more probes in the stack, which must be placed within the exhaust gas system, far enough away from the stack exit and sufficiently close to the engine to ensure that it is sampling a high temperature exhaust without any fresh air influence. The inlet of each probe must be far enough away from a multi-cylinder engine that the sample is representative of the average exhaust emissions from all cylinders. (In engines with multiple manifolds – V-type engines – sampling can be done from each manifold simultaneously and the results can be averaged.)

Some samplers are extraction samplers, meaning they remove a small volume of exhaust gas and process it within a measurement device and then exhaust the sample to atmosphere. Often the sampling lines for these instruments must be heated so that the instrument reads exhaust gas properties under the same conditions as in the stack. Other samplers generate an electrical signal at the probe that is analyzed by the instrument; these probes do not remove stack gases, but analyze the gas directly as it flows past each probe to the stack exit.

If there is any water injection in the stack for cooling or noise reduction, or if there are any exhaust gas treatment systems, the measurements must be made sufficiently downstream of these devices to allow representative mixing of stack gases so that analyzers are reading the average emissions.

4.3.2 Test Equipment

Most protocols define similar equipment requirements for measurement of gaseous and particulate emissions, typically based on the preferred sampling technology for each pollutant. However, other technologies that meet the standards of accuracy can also be used. The main point of this section is that different instruments are required to measure different exhaust emissions. Following are the ISO standard equipment specifications for the most likely exhaust species measured during a marine engine test (ISO 1996).

- HC – A heated flame ionization detector (HFID) for measuring hydrocarbons. The temperature shall be between 453 [Kelvin or K] and 473 K (180 °C to 200 °C) for non-methanol-fueled engines, and at 375 K to 395 K (102 °C to 122 °C) for methanol-fueled engines.
- CO, CO_2 – Non-dispersive Infrared (NDIR) detectors for the determination of carbon monoxide and carbon dioxide.
- NOx (NO, NO_2) – A chemiluminescent detector (CLD) or heated chemiluminescent detector (HCLD) measures oxides of nitrogen. If an HCLD is used, the extracted sample must be kept at a temperature of 328 K to 473 K (55 °C to 200 °C).

- O_2 – Oxygen is measured by a paramagnetic detector (PMD), a zirconium dioxide sensor (ZRDO), or an electrochemical sensor (ECS).
- PM – Particulate matter is generally a complex pollutant to measure, for reasons discussed above. A dilution of stack gas with atmospheric gas is required to allow for secondary particle formation and other processes that determine the size and properties of PM as exhaust gas mixes and cools in the atmosphere. Either partial dilution systems or full dilution systems can be used. To save space and reduce necessary instrument capacity, partial dilution systems split the exhaust stream then dilute a portion of the exhaust flow before the particulate sampling system. The full dilution system does essentially the same thing to the entire exhaust flow. The particle sampling system consists of a configuration of filters and a sampling pump that draws diluted exhaust gas through the filters.

Some protocols also specify analytical standards for ammonia, methane, methanol, and formaldehyde (ISO 1996). These tests may be of interest to some operators in certain regions where these pollutants are a significant air quality problem, but most engine tests do not include these without special reasons. Marine engines have also been tested for polycyclic aromatic hydrocarbons (PAHs), dioxins, and heavy metals – all considered micropollutants (Carlton, Danton et al. 1995). Heavy fuels do contain some heavy metals in trace amounts, and these emissions may become a focus of environmental policy for marine engines in the future. However, current understanding is that marine engines are not major emitters of these pollutants. (Fuel quality standards define maximum acceptable limits for certain metals, such as vanadium and aluminum, that can damage engines (ISO 1987).) Therefore, this report does not address testing for these pollutants, although providers of the sort of testing technology described here are generally knowledgeable of the appropriate testing standards.

4.3.3 <u>Test Operating Conditions</u>

Emission test protocols were originally developed for manufacturer test-bed measurements, and were later extended to in-service engine testing. Under test-bed conditions, a number of specific operating conditions are required so that routine testing of engine families and engines within a family are comparable. These operating conditions focus on fuel type and quality, on defined and repeatable load settings, and other laboratory conditions. However, in-service emissions protocols acknowledge that test-bed conditions may not be representative of in-service operation – particularly for marine engines. Measurement of in-service engine emissions may be necessary if any of the following conditions exist (ISO 1996):

1. **Test bed measurement cannot duplicate site conditions.** For example, if the actual fuel at the site (e.g., marine residual fuel) cannot be used at the test-bed location because of availability or environmental restrictions, or when ambient conditions at the test bed are not representative of site conditions (e.g., at sea trials);
2. **In-service measurement is necessary to evaluate actual and local pollution.** In this case test-cycles used at the test-bed facility may not be the same as actual or simulated operating conditions, but most protocols require that standard test cycles be followed as close as possible during the in-service test for later comparability with test bed measurements;

3. **Parties involved agree to site measurement as a substitute for test-bed measurement.** Under these conditions, specific tests may not represent average or typical values for a fleet of engines. Measured values under a unique duty cycle cannot be directly compared with test-best results at standard duty cycles because measured values depend on the duty cycles;
4. **In-service measurement is necessary to check the conformity of used or rebuilt engines to a standard.** Under this condition, an engine being tested must follow the same test cycles as those used for certification.

As discussed above, fuel properties vary with type of fuel. These fuel characteristics (e.g., density, viscosity, energy value, and element analysis [% Mass] of C, O, N, and S) influence the engine exhaust characteristics, so specifying the type and quality of the fuel used for the test is very important. Generally, a test-bed protocol uses a reference fuel; typically, marine engines are certified by manufactures on a diesel reference fuel (ISO 1997). However, for an in-service test, the test fuel should be the typical fuel for the engine and its application. EPA proposed regulations call for certification testing of large marine engines (EPA Category C3) to use marine residual fuel, or to correct test results for the additional fuel-based nitrogen in residual fuel (EPA 2002). Specific characteristics to include are listed in the universal data sheet reproduced from the ISO standard in the appendix (ISO 1996).

Marine engines operate on a variety of fuels that do not conform to the original manufacturers' test-bed certifications (ISO 1987). Moreover, recent research and demonstration efforts have focused on the potential for alternative cleaner fuels (with or without advanced propulsion alternatives) to reduce marine emissions. Some marine engines have already been tested on low-sulfur fuels, biodiesel fuels, and pretreated fuels (e.g., emulsifications). A list of example fuels used by or proposed as clean fuel alternatives for marine engines is provided in Table 4-1.

Table 4-1. Types of fuels that may be used in emissions tests

Class of Fuel	Examples
Diesel	ISO defines four standard grades for marine service Low sulfur diesel "Bio-diesel"
Heavy fuels	ISO defines fifteen residual grades for marine service
Gasoline	Standard Ethanol-blends Methanol-blends
Gases	Compressed natural gas (CNG) Liquid natural gas (LNG) Propane Hydrogen (mostly related to marine fuel cell research)

Protocols for marine engine testing may need to be revised to account for the different fuel characteristics if an alternative fuel is used. For example, emulsifications may include chemical additives not reflected in a standard test of the fuel before treatment. Also, natural gas and LPG engines in the heavy-duty emission regulations will require modified formulas for calculating the emissions and also specifications for the reference fuels (Nylund and Lawson 2000). And marine fuels may exceed the sulfur contents in reference fuels for which existing test procedures may have been validated (EPA 1999).[4] ISO standards provide a set of "Universal Analytical Data Sheets" for fuels, including natural gas, liquefied petroleum gas, motor gasolines, diesel fuels, distillate fuel oils, residual fuel oils, and crude oil (ISO 1997). Data sheets (an example is reproduced in the Appendix) like these can be used to report important fuel characteristics necessary to report accurate emissions results.

If the engine being tested is using a fuel pretreatment, that will have to be accounted for in the emissions test. For example, water/fuel emulsions have been demonstrated to reduce marine engine emissions (Corbett and Fischbeck 2002).[5] Other fuel pretreatment techniques include direct water injection (Silja Line Oy 1999), a technique marketed by manufacturer, Wärtsilä Corporation (http://www.wartsila.com/english/pdf/en_direct_water_inj.pdf) and perhaps other manufactures. To the degree that these treatments modify the energy value of the fuel or modify the fuel properties, these changes may need to be noted.

If the engine tested uses air pretreatment, such as turbocharging or charge air cooling (which is common) or humidification (which offers emissions reductions), then the exhaust gas properties will likely be affected. Turbocharging, for example, increases the mass of air flowing through the engine over a naturally aspirated engine. Using the carbon balance approach and depending on fuel consumption measurements and exhaust gas measurements, these techniques may not affect the testing protocol. However, some air pretreatment technologies designed to reduce emissions (e.g., intake air humidification) may require modification of certain analyses. An operator should inform the engine test contractor of any special air pretreatments outside of original engine specifications.

The effects of exhaust gas aftertreatment must also be considered in emissions testing. As vessels adopt new or retrofit engines with emissions control technologies, testing is expected to become more common. Technologies such as selective catalytic reduction (SCR) and catalytic filters for PM are inserted into the exhaust system to capture, remove, or react with exhaust pollutants. Test protocols require that exhaust samples be taken sufficiently downstream of an aftertreatment device.

Engine parameters must be carefully recorded during an in-service emission test. Generally, the parameter settings for an in-service test should not be modified from normal operations. This may differ from a test-bed certification test, where factory settings are typically chosen. Engine systems onboard vessels may need to be conditioned to ensure repeatable measurement results. For example, an engine may need to operate at a given load for some period to ensure that the stack temperatures are stable. Engine performance may change substantially if the timing is adjusted or after significant repairs or engine overhaul.

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[4] EPA suggests that ISO 8178 testing standards for PM have not been validated with fuel containing more than 0.8 percent sulfur by-weight.

[5] Some of these techniques include special formations, such as Purinox (www.lubrizol.com). A bibliography of articles on water/fuel emulsions is available at http://www.epa.gov/otaq/models/analysis/emulsion/emulbibl.pdf.

EPA expects that manufacturers can specify the range of adjustment across which the engine is certified to comply with the applicable emission standards (EPA 2002). This would allow a manufacturer to specify different fuel injection timing calibrations for different conditions.

4.3.4 Different Test Scopes

In this chapter on emission test fundamentals, we have described many of the basic elements that apply to all emission tests. Here, we discuss some of the possible differences between emission testing. These differences can arise because operators and regulators may not require a complete test, or may not be able to follow the test protocols exactly. Discussed above are two of the basic test scopes: Manufacturer (test-bed) measurements; and In-service (or at site) measurements. Manufacturer testing is typically done to certify a family of engines, and to maintain that certification. In-service testing can be done as an initial test, to substitute for test-bed measurements, or periodically to ensure continued compliance as equipment is maintained and upgraded.

A third type of measurement may be a simplified (or "quick look") test. EPA believes "that onboard emission equipment that is relatively inexpensive and easy to use could be used to verify that an engine is properly adjusted and is operating to the specifications of the engine manufacturer. [They] do not believe that it would be necessary to perform a complete certification-type emission test after each adjustment" (EPA 2002). This suggests that operators may be able to commission testing that is less expensive and rigorous than certification testing, which standard protocols describe. However, these tests may not provide enough detail to be comparable with test results from other engines in a fleet.

Most protocols specify that engines be tested under steady-state conditions at several test cycles ("test cycle" is defined in Section 2.2). Standard test cycles are defined to be representative of given engine applications (ISO 1996). For example, ISO standards apply different test cycles to engines in onroad motor vehicles, earth-moving machinery, diesel-powered engines, spark-ignited engines, constant speed engines, rail applications, lawn/garden equipment and marine vessels.

A test cycle is slightly different than a duty cycle. The duty cycle summarizes the percent of time an actual engine spends at various engine modes ("mode" is defined in Section 2.2). The test cycle for a category of engine service may not represent the duty cycle of a particular engine in that service. For example, research has shown that the duty cycle of inland river towboats may not be accurately represented by any of the marine test cycles defined by ISO (Corbett and Robinson 2001). The same may be true of ferry vessels, tugboats, and other workboats that do not operate according to the average marine test cycles.

Figure 4-2 compares the fraction of operations assigned to each mode based on observations and based on two ISO test cycles for marine service. For the vessel (referred to as Small Tow in the article), columns represent the best estimate of the duty cycle as observed during continuous emissions monitoring. The ISO E3 duty cycle does not define any test mode at idle, although this vessel operates under idle conditions more than half of the time. Both ISO E3 and E5 overestimate the amount of time this vessel operates at high loads.

The challenge with testing under steady state conditions is that pollutant formation during transient conditions (i.e., load changes) may not be well represented in steady-state tests. Particularly because test protocols require "preconditioning of the engine" (a term defined in Section 2.2), steady state tests assume that engine operation is predictable and that load changes are gradual. This may be generally true for larger cargo vessels, but many marine engines change load frequently during operation. Ferry vessels on short commuter routes are likely to spend more time at reduced speeds within port precautionary zones, maneuvering, or at idle during passenger load/discharge. And many workboats operate on different duty cycles from day to day, depending on their specific tasks (e.g., vessel assist versus transit, or upstream movement of loaded barge strings versus downstream movement of empties).

Because of these issues, many operators may be interested in emission testing that captures their actual emissions profile. Continuous emissions monitoring systems (CEMS) and constant volume sampling (CVS) systems have been developed for marine engine applications, adapted from stationary engine testing (Cooper and Andreasson 1999; Corbett and Robinson 2001). Some testing of marine engines has included continuous emissions monitoring, and researchers are working to make this comprehensive testing more affordable to operators. This type of testing may enable policy makers to design incentive programs that can subsidize the cost of new equipment through emission trading or fee reductions.

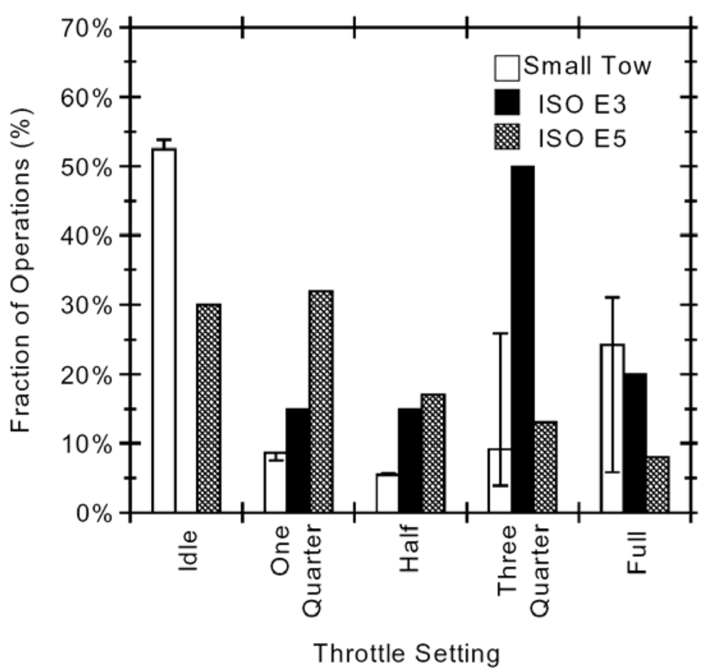

Figure 4-2. Comparison of Inland River Towboat, ISO E3, and ISO E5 duty cycles (Corbett and Robinson 2001). The vertical "error" bars indicate the potential maximum range in the duty cycle due to uncertainty in the peak propeller speed.

Figure 4-3 shows an example of results from a continuous emission test of a marine engine on a small towboat (Corbett and Robinson 2001). This vessel operates in "courier service" on upper inland rivers, under three basic operational modes: full throttle, maneuvering, and idle. Two of these three modes are illustrated in Figure 4-3. Full-throttle operation is shown during 0.5 and 2.5 hours (x-axis). Full throttle operations occur during transit between landings or locks on the rivers, typically with a barge or string of barges in tow. During this mode, the engines are operated at near steady-state, full-load conditions, except for occasional adjustments for navigation. A test protocol specifying preconditioning of the engine to stabilize engine and stack conditions could adequately describe this mode.

Maneuvering operations occur when picking up, dropping off, or rearranging tows of barges. Maneuvering is characterized by periods of idling broken by frequent and rapid changes in throttle setting to provide power and control. During maneuvering, this towboat spends most of its time at idle, but would not meet the preconditioning requirements under steady-state protocols. Under maneuvering conditions, actual emissions may vary from those measured by a steady-state protocol. These are the kinds of conditions that continuous testing is designed to measure.

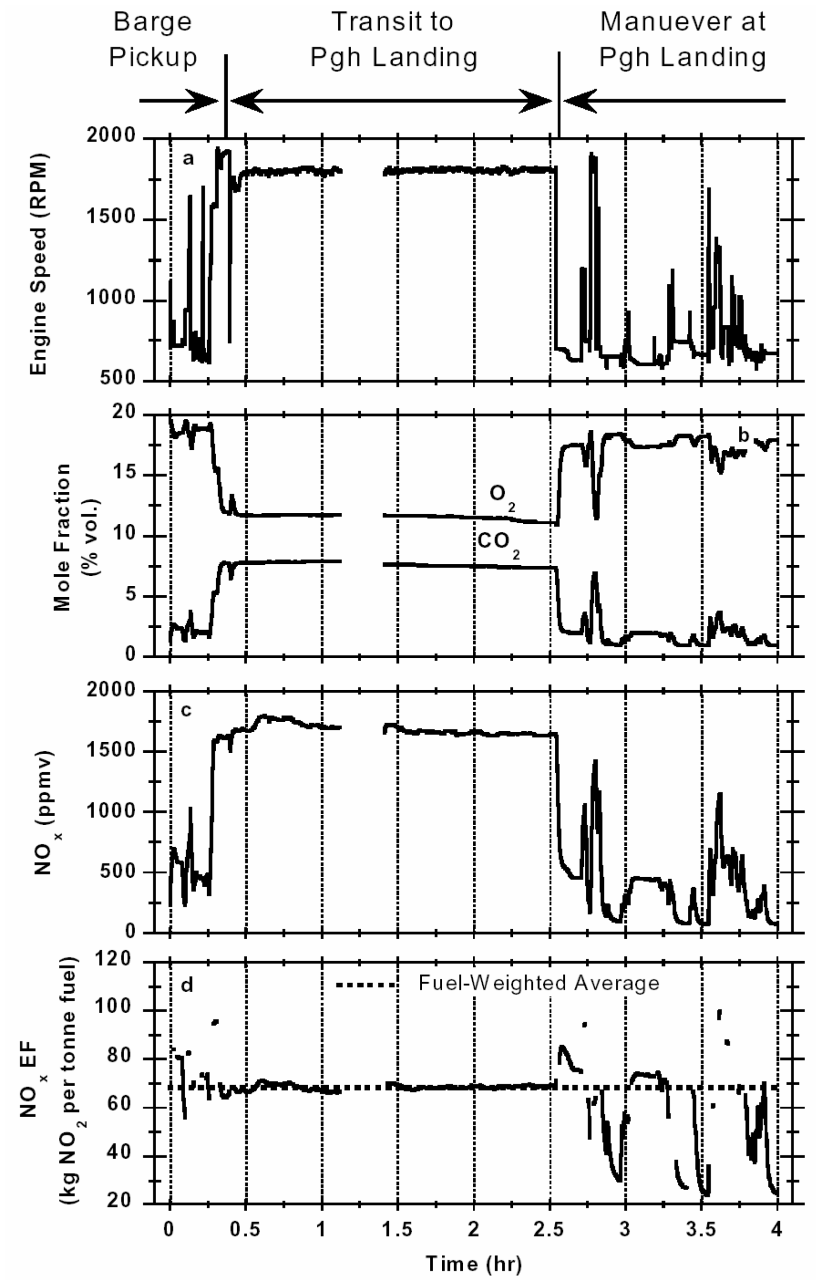

Figure 4-3. Time-resolved continuous measurements of (a) engine speed, (b) exhaust O2 and CO2 mole fraction, (c) exhaust NOx mole fraction, and (d) calculated NOx emission factor for a four-hour period of typical small towboat operations. The break in measurements between 1 and 1.5 hours corresponds to calibration of the gas analyzers. The horizontal line in (d) is the fuel-flow-weighted average NOx emission factor for this four-hour period. Further discussion of these test results can be found in (Corbett and Robinson 2001).

A comparison of steady-state measurements and continuous measurements is shown in Figure 4-4. While steady state emissions tests are useful for comparing "apples to apples" between different engines, this figure shows that continuous emissions monitoring may better describe emissions from actual operation. The steady-state measurements are comparable to those specified by EPA regulations and standard test protocols. Although the emissions during these steady-state measurements are somewhat lower than the averaged continuous measurements, they follow the same trend. Most importantly, the continuous measurements capture the significant idle periods that would not be accurately represented in the standard test cycles.

The term CEMS represents the total equipment necessary to determine the gas or particulate matter emission rate using analyzers and an algorithm for converting measurements into specific emissions (term defined in Section 2.2).[6] A CEMS test may prove to be less expensive than periodic testing, because the equipment only needs to be installed one time and fleet engineering staff can maintain the equipment as they do other engine control diagnostics. The CEMS data may also provide better quality data for predictive maintenance.

Technologies for CEMS are the same as for any on site test, except that the response time of analyzers must be faster to measure transient emissions during engine load changes. Also, a processor or software may need to be added that can convert measurement data rapidly into continuous emissions results. The CEMS approach is similar to other marine engine technology innovations, in that CEMS integrates a systems approach into emissions testing. Like electronic engine controls that monitor fuel flow and exhaust parameters to continuously monitor combustion efficiency, CEMS could become a tool for marine vessel operators to achieve optimal fuel economy and low emissions. Figure 4-5 illustrates a general schematic proposed by EPA for continuous onboard monitoring of NOx emissions (EPA 2002).

[6] A predictive emission monitoring system (PEMS) is the total equipment necessary for determining a gas emission rate using processor control devices to obtain predictive parameter measurements and an algorithm for predicting specific emissions within acceptable agreement with direct testing results. See www.epa.gov/ttn/emc/monitor.html for more information on PEMS applied to stationary sources. Early research has begun to apply them to marine vessels in Europe. See Cooper, D. A. and K. Andreasson, 1999.

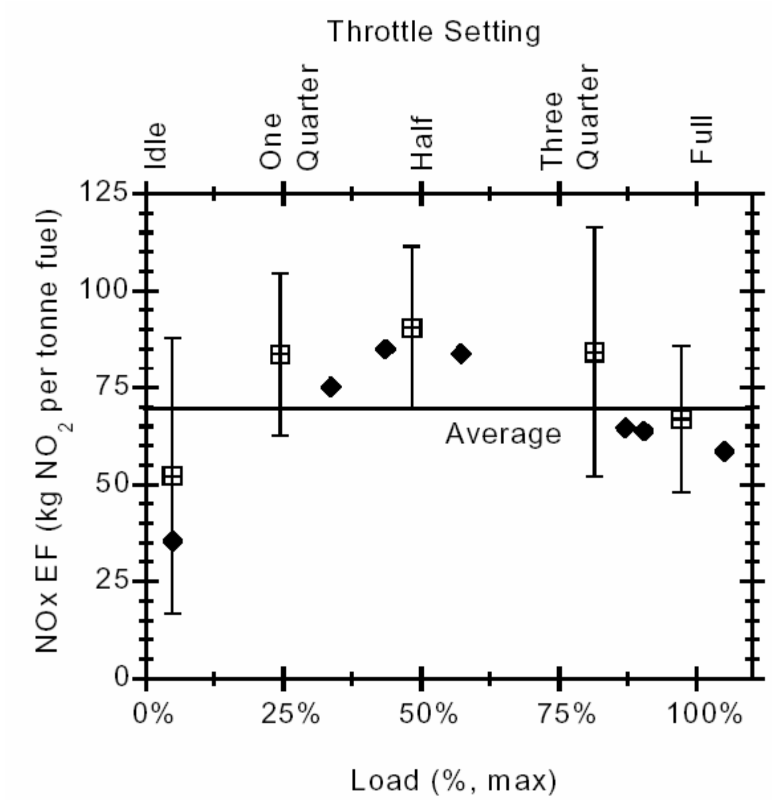

Figure 4-4. NOx emission factor as a function of engine load (Corbett and Robinson 2001). The square symbols are averages of continuous measurements over specified load ranges, and the solid diamond symbols represent measurements made during steady-state operations at specified throttle settings for 10-minute periods. The vertical "error" bars represent two standard deviations of the continuous measurements over the specified load ranges. The horizontal line is the fuel-flow-weighted average emission factor for NOx over the full operating range.

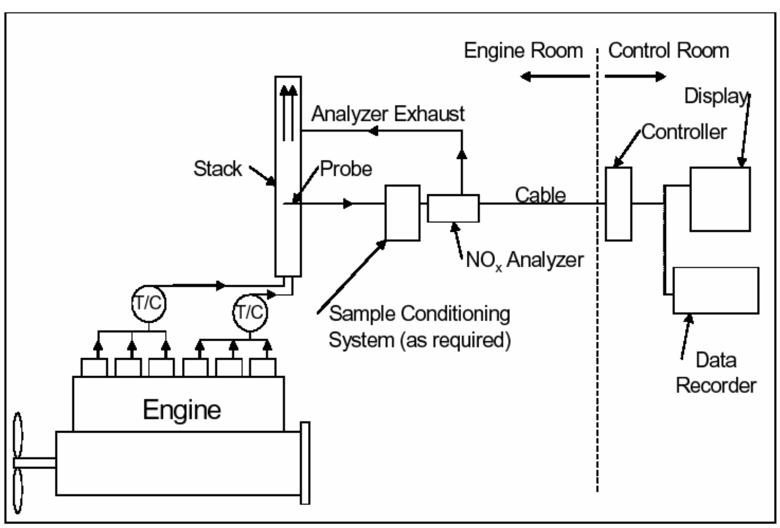

Figure 4-5. Example onboard NOx monitoring proposed for large (Category 3) engines (EPA 2002).

5 STANDARD PROTOCOLS

The International Organization for Standardization (ISO) provides the default standards for exhaust emission testing protocols, and nearly all marine engine test protocols adopt these procedures. Some of the later protocols condense or amend the ISO standards, and regulatory agencies have prescribed conditions for marine engine testing that are narrower than ISO. This chapter briefly summarizes ISO and makes general comparisons with the IMO NOx Technical Code and with current EPA regulations. This document does not provide a substitute for these protocols, as used by emissions testers. The purpose of this chapter is to inform vessel operators of the nature of these protocols so that they may be more informed when commissioning exhaust emissions testing on their marine engines.

5.1 ISO Standards

ISO is a worldwide federation of national standards bodies. In the United States, the American National Standards Institute (ANSI) serves as administrator and coordinator of the United States private sector voluntary standardization system, and is an ISO member. ANSI does not develop American National Standards (ANSs) independently; rather it facilitates development by establishing consensus among qualified groups (www.ansi.org). Similarly, ISO works through technical committees, consisting of interested ISO members, international organizations, and governmental agencies. Draft international standards adopted by these technical committees are accepted by ISO after approval by at least 75% of voting members.

ISO 8178, "Reciprocating Internal Combustion Engines – Exhaust Emission Measurement," contains nine parts (ISO 1996):

- Part 1: Test-bed measurement of gaseous and particulate exhaust emissions;
- Part 2: Measurement of gaseous and particulate exhaust emissions at site;
- Part 3: Definitions and methods of measurement of exhaust gas smoke under steady-state conditions;
- Part 4: Test cycles for different engine applications;
- Part 5: Test fuels;
- Part 6: Test report;
- Part 7: Engine family determination;
- Part 8: Engine group determination; and
- Part 9: Test-bed measurement of exhaust gas smoke emissions from engines used in non-road mobile machinery.

For in-service marine engine testing, the most important parts of ISO 8178 are Parts 2 and 4. These parts specify conditions and test cycles unique to in-service engine testing, and reference other parts for standard procedures that do not change from test-bed conditions. For example, many of the analytical calculations described in Part 1, required fuels data in Part 5, and standard reporting requirements in Part 6 may apply during in-service testing under ISO protocols.

Vendors providing exhaust emissions testing may modify their reporting formats, or may specify technologies that equal or exceed the accuracy and performance requirements specified in ISO, and still meet the ISO standards. Vendors may also certify that they meet EPA requirements for testing accuracy and performance. It is important that vessel operators understand when emissions tests will use modified ISO standards – especially if these modifications are not documented in other standards, such as the NOx Technical Code or EPA marine regulations (discussed below).

5.2 NO_x Technical Code

As part of the Maritime Pollution Conventions (MARPOL 73/78) at the International Maritime Organization (IMO), regulations to prevent air pollution from ships have been adopted. This agreement, referred to as Annex VI because it is the sixth set of regulations under MARPOL 73/78, requires new ships to meet NOx and SOx regulations. A resolution attached to Annex VI defines emissions testing standards for marine engines, called the NOx Technical Code (IMO 1998). According to the Code:

> "The purpose of this Code is to establish mandatory procedures for the testing, survey and certification of marine diesel engines which will enable engine manufacturers, shipowners and Administrations to ensure that all applicable marine diesel engines comply with the relevant limiting emission values of NOx as specified within regulation 13 of Annex VI to MARPOL 73/78. The difficulties of establishing with precision, the actual weighted average NOx emission of marine diesel engines in service on vessels have been recognised in formulating a simple, practical set of requirements in which the means to ensure compliance with the allowable NOx emissions, are defined" (IMO 1998).

While much of this Code exactly follows the ISO standards, there are several specific additions and/or modifications. For example, this Code defines when a ship's engine is subject to testing under Annex VI. This Code also describes survey and certification procedures that may not involve in-service emissions testing, but ensure engine compliance with Annex VI. For example, engines can be pre-certified prior to installation aboard ship. Moreover, the Code does not prescribe any methods for testing hydrocarbons, particulate matter, or other pollutants of concern.

The NOx Technical Code provides the shipowner the option of direct measurement of NOx emissions during engine operation. These are the procedures that closely replicate ISO standards. The Code also specifies the documentation and reporting that must be kept onboard the ship after a test is completed. The NOx Technical Code generally requires that tests represent normal engine operations, adjustments, and exhaust treatment performance.

Four test cycles are allowed for marine engine testing in the NOx Technical Code:

1. The ISO E2 test cycle is specified for main propulsion applications (both constant speed, and variable-pitch propeller sets).

2. The ISO E3 test cycle is specified for propeller-law-operated main and propeller-operated-auxiliary engines.
3. The ISO D2 test cycle is specified for constant-speed auxiliary engines.
4. The ISO C1 test cycle is specified for variable-speed, variable-load auxiliary engines, not included above.

The NOx Technical Code specifies a marine distillate (DM-grade marine fuel) as the reference fuel, unless otherwise agreed by IMO and when a suitable reference fuel is unavailable. This requirement is primarily focused on the expectation that engine manufacturers will pre-certify marine engines by family and/or group, and may not be easily applied to in-service emissions testing by operators.

In the NOx Technical Code, Chapter 6 defines procedures for demonstrating onboard compliance with IMO requirements. Under most conditions, this consists of a parameter check and technical survey to verify that engines continue to comply with NOx emission limits in Annex VI, Regulation 13. However, there are two acceptable measurement protocols allowed in the Code. The first is a simplified measurement method (described below), and the second is a direct measurement and monitoring method (i.e., the full certification test done onboard, similar to ISO).

The simplified measurement method is applied only for on-board confirmation tests and periodic and intermediate surveys of pre-certified engines. This method requires measurement of gaseous concentrations of NOx, together with O_2 and/or CO_2 and CO measurements under the appropriate test cycle. Not all engine-related parameters must be recorded, and greater deviation is allowed for certain engine parameters, such as engine torque, power, fuel consumption, air consumption, and exhaust gas flow. For example, specific fuel consumption curves from the manufacturer may substitute under the simplified test procedures for measured fuel flow. When using residual fuels, an estimate of the error caused by fuel curves and non-reference fuel must be included. Fuel-bound nitrogen (identified through fuel quality testing) will also need to be accounted for in the reported results. The Code allows for a simplified test to exceed standards by less than 10% only if there is insufficient information to determine the influence of residual fuel quality on NOx formation; this allowance does not apply to a pre-certification test.

5.3 EPA Regulations

EPA regulations (EPA 1999; EPA 2002) prescribe certain expectations and requirements for emission testing of marine engines, in both their existing rule (applicable to engines at or above 37 kW defined as Category 1 and 2 engines[7]) and their proposed rule (applicable to Category 3 engines). These regulations address in-use testing of marine engines without prescribing a full set of measurement protocols. Rather, EPA discusses when in-use testing may be encouraged or allowed, and sets certain requirements for test cycles and reference fuels.

[7] EPA defines Category 1 engines to have cylinder displacements less than 5 liters per cylinder, and Category 2 engines to have cylinder displacements from 5 liters (inclusive) to 30 liters per cylinder. Category 3 engines have cylinder volumes greater than or equal to 30 liters per cylinder.

For Category 1 and 2 engines, EPA states that manufacturer certification tests must follow similar land-based rules:

> "In this final rule we rely on previously established test procedures for land-based diesel engines. Specifically, we require that Category 1 marine engines be tested using the landbased nonroad procedures of 40 CFR Part 89, and that Category 2 marine engines be tested using the locomotive test procedures of 40 CFR Part 92. There are two reasons for using this approach. First, most manufacturers of marine diesel engines also manufacture landbased engines and will be equipped to test engines using these test procedures. Second, marine diesel engines are fundamentally similar to their landbased counterparts, and it is therefore appropriate to measure their emissions in the same way. In addition, the test procedures found in 40 CFR Parts 89 and 92 include flexibility for testing alternative-fuel engines. Some changes are nevertheless necessary. Manufacturers should be aware that the test procedures in MARPOL Annex VI are not equivalent to the test procedures described [in the EPA final rule]."

For Category 3 engines, the EPA proposed rule adopts the IMO NOx Technical Code for emissions testing, with certain modifications (EPA 2002). EPA requires that an explicit calculation be made to adjust for fuel-bound nitrogen; IMO standards allow for a 10-percent increase in emissions when testing with residual fuel, which makes the fuel correction a function of engine speed (EPA 2002). EPA requires the same test cycles for in-use testing of Category 3 engines as the NOx Technical Code. (Note that EPA test cycles for smaller marine engines may follow on-road or locomotive test protocols, as discussed above.)

EPA also suggests that certain parameters on very large marine engines be calculated rather than directly measured. "Annex VI allows g/kW-hr emission rates to be calculated using measured exhaust flow rates. However, [EPA does] not believe that exhaust can be reliably measured for Category 3 engines. Measuring exhaust flow rates in general is difficult due to the high temperatures and the variability of exhaust temperatures. [EPA] believe[s] that it would be even more difficult for very large engines. Exhaust stacks for Category 3 engines can be over a meter in diameter, which allows for significant spatial variation in the flow rate. Therefore, [EPA proposes] that exhaust flow rates be calculated using measured fuel flow rates" (EPA 1999).

6 WHAT TO SPECIFY FOR EMISSIONS TESTING

Perhaps the most important information in specifying an emissions test, is determining what information must be reported and how that information will be used by the operator or sponsoring agency. The emission test report must provide the information necessary to document the objectives of the test and determine whether proper procedures were used to accomplish these objectives (EPA 1998). An emissions test plan summary would include a brief summary that identifies or states, as applicable, the following:

1. Responsible groups (participating organizations)
2. Overall purpose of the emission test
3. Regulations, if applicable

4. Operator and owner of vessel
5. Name of vessel
6. Test location
7. Air pollution control equipment, if applicable
8. Emission points and sampling locations
9. Pollutants to be measured
10. Test plan and test procedure
11. Dates of emission testing

Vessel operators should identify certain specifications when requesting an emissions test. In general, an emission test procedure consists of the following elements (Nylund and Lawson 2000):

- Requirements for documenting the ambient conditions
- A defined speed/load pattern for the vehicle/engine
- Reference fuel or documentation of in-service fuel properties
- Measuring apparatus, including accuracy and response rates
- Gaseous component concentrations
- Particulate mass emission or smoke density
- Exhaust gas flow (measured directly or indirectly)
- Calibration gases
- Calculation procedures

Operators are recommended to require that vendors submit an emission test plan providing information on each of these elements, or that vendors follow an existing plan as described in Section 5. The contents of the test plan serve as the foundation for the test report. Requiring that emission tests follow a standard protocol, operators can specify most test elements. When requesting a steady-state test of engine exhaust emissions, operators are recommended to reference ISO or IMO test protocols. If the test results will be used to demonstrate compliance with an existing regulation (mandatory or voluntary), the IMO (and/or EPA) test cycles and any unique requirements under applicable state or local regulations should be specified.

This guidance document recommends that operators include steady-state test results in all specifications, unless the cost or scope of the test makes this infeasible. Steady-state testing is the conventional testing described by most standards and regulations, and provides the most comparable emissions results between different engines on different vessels. Steady-state testing also can be used to compare to transient emissions testing and continuous emissions testing methods, all of which can use common instrumentation.

Depending on the type of information required by the operator (or funding agency), some additions or modifications should be called out when necessary. If a test will be made on an engine using residual fuel, or using marine distillates different from reference fuels specified by test protocols, then fuel properties must be quantified and reported.

When specifying a test that includes other information beyond steady-state emissions, operators may need to specify additional requirements. For transient emissions and continuous emissions monitoring, analyzer instruments must have adequate response time to accurately capture rapid changes in exhaust characteristics. Operators should require that vendor proposals include information on instrument response times, that vendors certify all instruments (e.g., for testing of multiple pollutants) have similar or compatible response rates, and that engine parameters will be measured with similar frequency and accuracy.

Operators who are specifying a test that records engine parameters and emissions data continuously may also want to require vendors to evaluate the observed (in-use) duty cycle and compare it to the specified test cycles required in standards and regulation. This will enable operators to ensure that the test cycles provide an adequate representation of actual service. The vendor may also be able to produce a comparison of the specific emission rate resulting from test cycle and duty cycle.

Measurement systems should be specified to conform to standard protocol requirements. These requirements identify preferred types of analyzers, and required performance accuracy. Since existing protocols allow for substitute instruments as long as they meet the same accuracy of performance, an operator can simply specify that instruments must meet these performance requirements and require the vendor to certify this in their reporting of results.

An operator should also require that appropriate calibration, repetition of measurements, and quality control be documented. Any problems with calibration should be noted. In the test report, any field test changes or modifications (particularly other than those specified by the operator and documented in the test plan) should be noted. Vendors should document whether field changes may reduce the reliability or accuracy of the results. For example, due to vessel operations a marine engine may not be operated at a given test cycle for sufficient time to ensure stabilization on one of the repeated steady-state tests; this information may not significantly affect results but it should be documented in the test report.

7 HOW TO USE A TEST ANALYSIS

When an operator receives an emissions test report for a specific marine engine, that analysis can serve several purposes. Operators may want to evaluate data for internal purposes, related to capital investment or to ensure compliance with expected engine performance. Test results can be compared to past tests for the same engine to evaluate whether engine hours and wear are affecting emissions rates (and fuel economy). Results reported by different vendors or using different instruments may be compared to demonstrate consistency between methods, technologies, or procedures. These sorts of comparisons can be useful in identifying least-cost test procedures for operators.

Local, state, or federal agencies may be interested in test results to demonstrate compliance with mandatory or voluntary standards. Regulators may also want to use the data to strengthen the statistical quality of industry average emission factors (specific emissions averaged over a fleet). Regulators may also use results provided by operators to revise emissions requirements so that standards are more cost-effective or better achieve air quality objectives. This may include using emissions testing of vessels with emissions control to verify reductions. Such information is important for policy makers (particularly at state and local levels) who are designing incentive programs for innovations in vessel, port, and cargo technologies. Operators may support public policy efforts to achieve better performance through modernization, and improving the quality of emissions knowledge may be an effective way for operators to contribute to these efforts.

To highlight the value of quality test data, two examples are provided from a recent IMO report. First, current testing of large, oceangoing vessels demonstrates that, on average, existing vessels without emissions control equipment may already meet IMO NOx standards (defined in Annex VI of MARPOL, and discussed in Section 2). Figure 7-1 presents specific NOx emissions for many marine engines. These engines were tested in-service on existing ships prior to 2000; in other words, none of these engines are designed and certified to be IMO compliant. This data shows that about half of the engines tested meet IMO standards and that half of the engines exceed IMO standards.

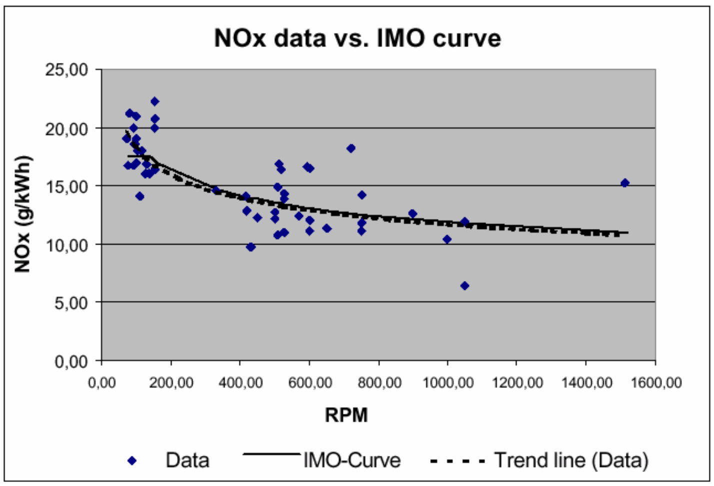

Figure 7-1. Comparison of individual engine test emissions results and aggregate trend line for in-service engines with IMO NOx standards (Skjølsvik, Andersen et al. 2000).

What this figure does not explain is whether this variability among engines is a function of engine age, maintenance, operation, or design. In order to achieve these goals, test data from many engines must be aggregated with sufficient detail to statistically evaluate potential reasons that explain the variation.

The maritime industry and policy makers are interested in at least three ways to aggregate test data. First, test data can be aggregated over time for one or more vessels to determine emission performance changes as engines wear. Some policy makers expect that marine engine emissions will increase with age, but emissions of certain pollutants such as NOx may slightly decrease as cylinder wear decreases maximum temperatures and pressures of combustion. Second, test data can be aggregated across a fleet of similar engine types and/or similar vessel types. Stakeholders would like to understand whether emissions from inland river towboats with similar sized engines tend to follow the same profile as the inland river towboat described in Section 5.

Perhaps the type of service operation is a larger determinant of emissions than engine model for vessels with very different duty cycles. Third, test data can be aggregated across multiple fleets to provide general emissions factors within some confidence bounds. This is how larger regional, national, and global inventories of emissions are estimated. For onroad sources, EPA has developed very sophisticated models to account for known engine characteristics, vehicle age, and operating profiles. Improved models could be developed for maritime transportation with the proper test data as a basis.

7.1 Methods for Consistent Data Analysis

The most important requirement for aggregation and comparison of test results is good data quality. Existing test protocols and standard reporting formats are designed to ensure that data analyses for multiple engines can be compiled. Given a set of complete emission test results, the statistical analysis to combine these data is straightforward. This report is not intended to instruct the operator who commissions a test on the technical details of statistics; rather the intent is to inform operators who commission engine tests that data quality enables consistent data analysis.

By reporting the results of repeated testing of emissions at steady-state test cycles, and/or by providing complete information on continuous emissions testing, the composite emissions factor results include information about variability. This information can be used to estimate standard deviations on the specific emissions for a single engine, and for a compilation of engine data. An example of the value of this approach is illustrated in Figure 7-2.

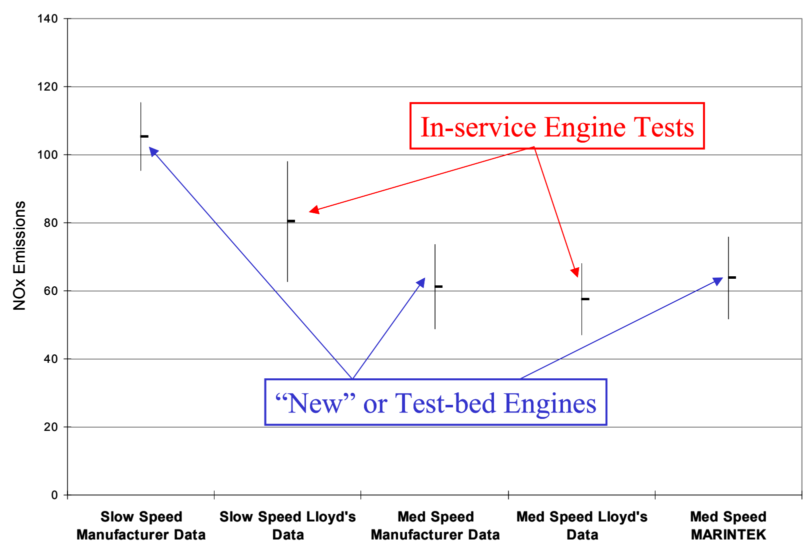

Figure 7-2. Comparison of Manufacturer and In-Service Engine Tests for Slow-Speed and Medium-Speed Engines. NOx estimates shown in kilograms per tonne fuel (tick marks) with one standard deviation (vertical bars). Adapted from (Skjølsvik, Andersen et al. 2000).

This figure shows the results of statistical comparisons between multiple engine tests by manufacturers of new engines under test-bed conditions and multiple in-service engines. Engine data was compiled by MARINTEK and summarized in the IMO Study of Greenhouse Gases From Ships (Skjølsvik, Andersen et al. 2000). The data are presented separately for slow-speed engines and for medium-speed engines. One standard deviation is shown for each data set.

For medium-speed engines, manufacturer data compares very well with in-service data and with MARINTEK's own testing. However, slow-speed engines tested in service tend to have lower emissions per tonne fuel, and greater variability. It should be noted that these comparisons are based on limited test data, and these comparisons may change as more marine engines are tested.

7.2 A Clearinghouse Concept for Reporting Results of Engine Emissions Testing

The Maritime Administration (MARAD) encourages operators to inquire about emissions testing and explore whether direct measurement of exhaust emissions may meet important goals for the U.S. maritime industry. Under its mission to research, develop, and disseminate information on energy and emissions technology and technology applications, MARAD hopes to promote or directly establish a clearinghouse for emission test data. This clearinghouse would receive test data from marine engines in service in U.S. navigable waters (including international shipping lanes, ports and harbors, lakes, and inland rivers). MARAD encourages operators use these testing and reporting guidelines when obtaining emissions testing, so that data provided to a common repository or published in reports and journals can be aggregated to help and inform industry and government stakeholders interested in improving the environmental performance of the maritime transportation system.

8 BIBLIOGRAPHY

8.1 Emissions protocols/standards

- ISO 8178
- NO_X Technical Code
- EPA Regulations

8.2 Report References

California Air Resources Board (1994). 1994 California State Implementation Plan: Volume IV, Air Resources Board. **2001**.

Carlton, J. S., S. D. Danton, et al. (1995). Marine Exhaust Emissions Research Programme. London, Lloyd's Register Engineering Services.

Cooper, D. A. and K. Andreasson (1999). "Predictive NOx Emission Monitoring on Board a Passenger Ferry." Atmospheric Environment **33**(28): 4637.

Corbett, J. J. and P. S. Fischbeck (2002). "Commercial Marine Emissions and Life-Cycle Analysis of Retrofit Controls in a Changing Science and Policy Environment." Naval Engineers Journal **114**(1): 93-106.

Corbett, J. J. and A. L. Robinson (2001). "Measurements of NOx Emissions and In-Service Duty Cycle from a Towboat Operating on the Inland River System." Environmental Science & Technology **35**(7): 1343-1349.

DOE (1995). National Energy Policy Plan, Department of Energy. **2001**.

EPA (1998). 40 CFR Part 94: Control of Emissions of Air Pollution From New CI Marine Engines at or Above 37 kw; Proposed Rule. Ann Arbor, MI, Environmental Protection Agency.

EPA (1998). National Air Pollutant Emission Trends Update, 1970-1997. Washington, DC, U.S. EPA.

EPA (1998). Preparation and Review of Emission Test Reports, Emission Measurement Center Guideline Document (GD-043). Ann Arbor, MI, United States Environmental Protection Agency**:** 42.

EPA (1999). 40 CFR Parts 89, 92, and 94: Control of Emissions of Air Pollution from New CI Marine Engines at or above 37 kW, Final Rule. Washington, DC, Environmental Protection Agency.

EPA (1999). Final Regulatory Impact Analysis: Control of Emissions From Compression-Ignition Marine Engines. Ann Arbor, MI, U.S. EPA Office of Air and Radiation; Office of Mobile Sources; Engine Programs and Compliance Division**:** 132.

EPA (2002). 40 CFR Part 94: Control of Emissions of Air Pollution From New Marine Compression-Ignition Engines at or Above 30 Liters/Cylinder; Proposed Rule. Washington, DC, U.S. Environmental Protection Agency. **67:** 37548-37608.

EPA (2002). Draft Regulatory Support Document: Control of Emissions from Compression-Ignition Marine Diesel Engines At Or Above 30 liters per cylinder. Ann Arbor, MI, U.S. EPA**:** 157.

Farrell, A. E., D. W. Keith, et al. (in press). "A strategy for introducing hydrogen into transportation." Energy Policy.

Health Effects Institutes, Diesel Epidemiology Working Group, et al. (2002). Research Directions to Improve Estimates of Human Exposure and Risk from Diesel Exhaust. Boston, MA, Health Effects Institute**:** 233.

Heywood, J. B. (1988). Internal Combustin Engine Fundamentals. New York, NY, McGraw-Hill, Inc.
IMO (1998). Annex VI of MARPOL 73/78 and NOx Technical Code. London, UK, International Maritime Organization.
ISO (1987). International Standard, Petroleum Products - Fuels (class F) - Specifications of Marine Fuels. Geneva, Switzerland, International Organization for Standardization.
ISO (1996). Reciprocating Internal Combustion Engines -- Exhaust Emission Measurement -- Part 1: Test-bed Measurement of Gaseous and Particulate Exhaust Emissions. Geneva, Switzerland, International Organization for Standardization**:** 94.
ISO (1996). Reciprocating Internal Combustion Engines -- Exhaust Emission Measurement -- Part 4: Test Cycles for Different Engine Applications. Geneva, Switzerland, International Organization for Standardization.
ISO (1997). Reciprocating Internal Combustion Engines -- Exhaust Emission Measurement -- Part 5: Test Fuels. Geneva, Switzerland, International Organization for Standardization**:** 30.
Keith, D. W. (2000). "Geoengineering the Climate: History and Prospect." accepted for publication in Annual Reviews of Energy and the Environment **25**.
Keith, D. W. and E. A. Parson (2000). A Breakthrough in Climate Change Policy? Scientific American**:** 78-79.
Los Angeles Board of Harbor Commissioners, A. Yamaki, et al. (2001). Memorandum of Understanding for the Use of Emission Reductions from Voluntary Commercial Cargo Ship Speed Reductions to Meet the Goals of the 1994 State Implementation Plan and the 1997 South Coast Air Quality Management Plan for Marine Vessel Emissions Control Strategies. Los Angeles, Los Angeles Board of Harbor Commissioners, U.S. Environmental Protection Agency, State of California Air Resources Board, South Coast Air Quality Management District, City of Long Beach, City of Los Angeles, Steamship Association of Southern California, the Pacific Merchant Shipping Association, and the Marine Exchange of LA/LB Harbor**:** 4.
Nylund, N.-O. and A. Lawson (2000). Exhaust Emissions from Natural Gas Vehicles: Issues related to engine performance, exhaust emissions and environmental impacts, A report prepared for the IANGV Technical Committee. Auckland, New Zealand, IANGV.
Port of Los Angeles (2002). Press Release: The Port of Los Angeles Funds $2.8 Million Clean Air Program. Port of Los Angeles. Los Angeles.
Silja Line Oy (1999). Environmental Report 1999. Helsinki, Finland**:** 36.
Skjølsvik, K. O., A. B. Andersen, et al. (2000). Study of Greenhouse Gas Emissions from Ships (MEPC 45/8 Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships). Trondheim, Norway, MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas.
TNRCC (1999). Revisions to the State Implementation Plan for the Control of Ozone Pollution. Austin, TX, Texas Natural Resource Conservation Commission**:** 74.
Turns, S. R. (1996). An Introduction To Combustion. New York, NY, McGraw-Hill, Inc.
URS Corporation Draft Program Environmental Impact Report: Expansion of Ferry Transit Service in the San Francisco Bay Area. San Francisco, Water Transit Authority**:** 501.
Water Transit Authority (2002). Community Advisory Committee Emission Testing Results. San Francisco, Water Transit Authority**:** 15.

Weaver, C. S. and M. V. Balam-Almanza (2001). Development of the 'RAVEM' Ride-Along Vehicle Emission Measurement System for Gaseous and Particulate Emissions. SAE International Fall Fuels & Lubricants Meeting & Exhibition, San Antonio, TX, USA, Society of Automotive Engineers.

9 APPENDIX ONE: Sample Test Report from IMO NOx Technical Code

Emissions Test Report No. .... **Engine Information*** **Sheet 1/5**

Engine		
Manufacturer		
Engine type		
Family or Group identification		
Serial number		
Rated speed		rpm
Rated power		kW
Intermediate speed		rpm
Maximum torque at intermediate speed		Nm
Static injection timing		deg CA BTDC
Electronic injection control	no: yes:	
Variable injection timing	no: yes:	
Variable turbocharger geometry	no: yes:	
Bore		mm
Stroke		mm
Nominal compression ratio		
Mean effective pressure, at rated power		kPa
Maximum cylinder pressure, at rated power		kPa
Cylinder number and configuration	Number: V:	In-line
Auxiliaries		
Specified ambient conditions:		
Maximum seawater temperature		°C
Maximum charge air temperature, if applicable		°C
Cooling system spec. intermediate cooler	no: yes:	
Cooling system spec. charge air stages		
Low/high temperature cooling system set points	/	°C
Maximum inlet depression		kPa
Maximum exhaust back pressure		kPa
Fuel oil specification		
Fuel oil temperature		°C
Lubricating oil specification		
Application/Intended for:		
Customer		
Final application/installation, Ship		
Final application/installation, Engine	Main: Aux:	

Emissions test results:					
Cycle					
NO_x					g/kWh
Test identification					
Date/time					

Test site/bench	
Test number	
Surveyor	
Date and Place of report	
Signature	

* If applicable

Emissions Test Report No. .... **Engine Family Information*** **Sheet 2/5**

Engine Family Information/Group Information (Common specifications)	
Combustion cycle	2 stroke cycle/4 stroke cycle
Cooling medium	air/water
Cylinder configuration	Required to be written, only if the exhaust cleaning devices are applied
Method of aspiration	natural aspired/pressure charged
Fuel type to be used on board	distillate/distillate or heavy fuel/dual
Combustion chamber	Open chamber/divided chamber
Valve port configuration	Cylinder head/cylinder wall
Valve port size and number	
Fuel system type	

Miscellaneous features:	
Exhaust gas recirculation	no / yes
Water injection/emulsion	no / yes
Air injection	no / yes
Charge cooling system	no / yes
Exhaust after-treatment	no / yes
Exhaust after-treatment type	
Dual fuel	no / yes

Engine Family/Group Information (Selection of parent engine for test bed test)					
Family /Group Identification					
Method of pressure charging					
Charge air cooling system					
Criteria of the Selection (specify)	Maximum fuel delivery rate / another method (specify)				
Number of cylinder					
Max. rated power per cylinder					
Rated speed					
Injection timing (range)					
Max. fuel parent engine					
Selected parent engine					Parent
Application					

* If applicable

Emissions Test Report No. .... **Test Cell Information*** **Sheet 3/5**

Exhaust Pipe	
Diameter	mm
Length	m
Insulation	no yes:
Probe location	
Remark	

Measurement equipment					
	Manufacturer	Model	Measurement ranges	Calibration	
				Span gas conc.	Deviation
Analyser					
NO_x Analyser			ppm		%
CO Analyser			ppm		%
CO2 Analyser			%		%
O2 Analyser			%		%
HC Analyser			ppm		%
Speed			rpm		%
Torque			Nm		%
Power, if applicable			kW		%
Fuel flow					%
Air flow					%
Exhaust flow					%
Temperatures					
Coolant			°C		°C
Lubricant			°C		°C
Exhaust gas			°C		°C
Inlet air			°C		°C
Intercooled air			°C		°C
Fuel			°C		°C
Pressures					
Exhaust gas			kPa		%
Inlet manifold			kPa		%
Atmospheric			kPa		%
Vapour pressure					
Intake air			kPa		%
Humidity					
Intake air			%		%

Fuel Characteristics

Fuel type				
Fuel properties:			**Fuel elemental analysis**	
Density	ISO 3675	kg/l	Carbon	% mass
Viscosity	ISO 3104	mm^2/s	Hydrogen	% mass
			Nitrogen	% mass
			Oxygen	% mass
			Sulphur	% mass
			LHV/Hu	MJ/kg

* If applicable

Emissions Test Report No. .... **Ambient and Gaseous Emissions Data*** **Sheet** 4/5

Mode		1	2	3	4	5	6	7	8	9	10
Power/Torque	%										
Speed	%										
Time at beginning of mode											

Ambient Data											
Atmospheric pressure	kPa										
Intake air temperature	°C										
Intake air humidity	g/kg										
Atmospheric factor (fa)											

Gaseous Emissions Data:											
NO_x concentration dry/wet	ppm										
CO concentration dry/wet	ppm										
CO2 concentration dry/wet	%										
O2 concentration dry/wet	%										
HC concentration dry/wet	ppm										
NO_x humidity correction factor											
Fuel specification factor (FFH)											
Dry/wet correction factor											
NO_x mass flow	kg/h										
CO mass flow	kg/h										
CO2 mass flow	kg/h										
O2 mass flow	kg/h										
HC mass flow	kg/h										
SO2 mass flow	kg/h										
NO_x specific	g/kWh										

* If applicable

Emissions Test Report No. .... **Engine Test Data*** **Sheet 5/5**

Mode		1	2	3	4	5	6	7	8	9	10
Power/Torque	%										
Speed	%										
Time at beginning of mode											

Engine Data											
Speed	rpm										
Auxiliary power	kW										
Dynamometer setting	kW										
Power	kW										
Mean effective pressure	bar										
Fuel rack	mm										
Uncorrected spec. fuel consumption	g/kWh										
Fuel flow	kg/h										
Air flow	kg/h										
Exhaust flow (gexhw)	kg/h										
Exhaust temperature	°C										
Exhaust back pressure	mbar										
Cylinder Coolant temperature out	°C										
Cylinder Coolant temperature in	°C										
Cylinder Coolant pressure	bar										
Temperature intercooled air	°C										
Lubricant temperature	°C										
Lubricant pressure	bar										
Inlet depression	mbar										

* If applicable

10 APPENDIX TWO: Local Protocol Example

Santa Barbara County Air Pollution Control District Diesel Marine Vessel Emissions Testing Protocol, 2001

Diesel Marine Vessel Emissions Testing Protocol

Submitted to:
California Air Resources Board
1001 I Street
Sacramento, California 95814
Attn: Lucina Negrete
(916) 327-2938

Submitted by:
Santa Barbara County Air Pollution Control District
26 Castilian Drive, B-23
Goleta, California 93117
Attn: Eric Peterson
(805) 961-8824

February 2001

Santa Barbara County Air Pollution Control District
Diesel Marine Vessel Emissions Testing Protocol

Table of Contents

1. Purpose

This protocol documents the testing procedures to be used for determining baseline NOx emissions from existing diesel marine engines using a portable NOx analyzer for Carl Moyer Air Quality Standards Attainment Program ("Carl Moyer Program") projects.

2. Background

California Air Resources Board (CARB) Carl Moyer Program Guidelines contain default emission factors for estimating baseline emissions from diesel powered marine vessels. Alternatively, CARB has allowed emission factors derived from in-situ source testing to be used to estimate baseline emissions from marine engines. Due to the need to establish baseline emission levels prior to the repowering of the vessel, emissions testing will be performed with the existing engine still in the boat. This protocol outlines the procedures to be used for establishing baseline NOx emissions from in-situ testing.

3. Emissions Testing Equipment

3.1 Instrument Description

Instruments will be designed to meet the requirements of EPA Conditional Test Methods 022A, 030 or 034 [1]. Other instruments may be used as approved by CARB on a case-by-case basis.

3.2 Calibration and Quality Assurance Procedures

The portable NOx analyzer will be calibrated prior to each test consistent with manufacturer's recommendations and EPA Conditional Test Methods 022, 030, or 034, as appropriate.

Generally speaking, the instrument will be calibrated prior to each use, and then checked for accuracy, linearity, drift, and interference before and after each emissions test. If multiple boats are to be tested within a short period of time (e.g., 2 – 3 days) , post-test checks of the instrument need not be performed until after the last engine has been tested.

To prevent damage to the analyzer when testing engines that have wet exhaust systems (i.e., exhaust systems that emit engine cooling water and emissions), a water knock-out system will be used to prevent liquid water from being introduced to the analyzer. If such a water knockout system is used during testing, the calibration and accuracy checks will be performed with the system in place to ensure that the knockout system does not affect emission readings.

The results of instrument calibration, calibration/zero drift, and sampling system check will be recorded on a standardized form as appropriate for the analyzer being calibrated. An example instrument calibration and interference response recordkeeping form is included as Attachment A.

[1] These Conditional Test Methods, and others, are available on the EPA' website at www.epa.gov/ttn/emc/ctm.html.

4. Engine Test Cycle

Emissions testing for main propulsion engines will be performed using ISO 8178, Test Cycle Type E3: Heavy Duty Marine Engines (Attachment B). This test cycle establishes engine load test points based on the propeller law for heavy duty marine engines, without limitation to the length of the vessel. Test Cycle E3 emission test points and weighting factors are as follows:

Specification	Units	Mode			
		1	**2**	**3**	**4**
Engine Speed	Percent of max RPM	100	91	80	63
Engine Load	Percent of max horsepower	100	75	50	25
Weighting Factor	None	0.2	0.5	0.15	0.15

For each engine, the maximum RPM (Mode 1) will be based on the maximum safe continuous engine RPM for each engine, as configured in the vessel. The engine RPM for test Modes 2, 3 and 4 will be determined based on the maximum achievable RPM determined for Mode 1 multiplied by the recommended percentage of maximum RPM per the E-3 test cycle. Manufacturer's engine propeller power curves will then be used to determine fuel consumption in each mode. An example propeller power curve with E-3 test points is provided in Attachment C.

Emissions testing for auxiliary engines, or main engines that are used to power auxiliary equipment when the vessel is not underway, will be performed at a single steady-state mode that is representative of the load that the engine is typically subjected to.

Test length will be ten (10) minutes per mode. Test lengths may be extended if necessary to achieve a proper test. Emissions measurements will be made during the last 3 minutes of each test run. Emissions readings will be recorded at approximately 1 minute intervals starting on the eighth minute of the run. The three one-minute readings will be averaged to determine the emissions for that mode. For main propulsion engine tests, the vessels will be tested while cruising under typical sea conditions. Auxiliary engine tests may performed at dockside.

5. Data Collection

The following information will be recorded for each boat (example emissions test data recording forms for both main and auxiliary engine testing is included as Attachment D):

<u>Vessel Description</u>

- Vessel name
- Vessel usage
- Manufacturer
- Year of manufacturer

- ❖ Length
- ❖ Displacement (weight)
- ❖ Hull construction
- ❖ Type of hull (planing, semi-planing, or displacement)
- ❖ Engine Manufacturer
- ❖ Engine Model
- ❖ Manufacturer's Maximum Recommended Continuous RPM
- ❖ Year of engine manufacture
- ❖ Exhaust type (wet or dry)

Emissions Test Data:
- ❖ Test Date
- ❖ Ambient weather and sea conditions
- ❖ NO concentration in exhaust (ppm) for each mode
- ❖ NO2 concentration in exhaust (ppm) for each mode
- ❖ O2 concentration in exhaust (percent) for each mode
- ❖ Vessel speed in each mode
- ❖ Engine RPM in each mode

6. Emission Calculations

NOx emissions will be calculated in terms of grams/brake horsepower-hr. The exhaust gas flow rate required to calculate mass emissions rate will be computed from the F-Factor method described in EPA Method 19. The following equation will be used to calculate the NOx emission rate:

NOx (g/hr) = Stoichiometric Exhaust (SCF/hr) * O_2 Correction * NO_x Density (g/SCF)

Where:

Stoichiometric Exhaust = F * HHV * FC

F	=	EPA F Factor [2]		
	=	9,190 SCF/10^6 Btu (dry pollutant measurement basis)		
	=	10,320 SCF/10^6 Btu (wet pollutant measurement basis)		
HHV	=	Fuel Higher Heating Value	=	138,220 btu/gal [3]
FC	=	Fuel Consumption	=	gal/hr [4]

O_2 Correction	**=**	**20.9 / (20.9 – O2)**	(dry pollutant measurement basis)
	=	**20.9 / (20.9*(1-Bwa) -O2)**	(wet pollutant measurement basis)

[2] CFR 40, Part 60, Method 19, Table 91-1, "F Factors for Various Fuels".

[3] Based on independent laboratory analysis of diesel fuel from Santa Barbara Harbor fuel dock, October, 1998. In lieu of this value, HHV may determined from fuel samples taken at time of testing.

[4] Brake Specific Fuel Consumption will be based on manufacturer engine propeller curves at the appropriate test cycle RPM.

O_2	=	Percent Oxygen in Exhaust	=	Measured during testing
Bwa	=	moisture fraction of ambient air	=	Measured during testing[5]

NOx Density = **NOx * MW * UC / SV**

NOx	=	NOx concentration (ppm)	=	Measured during testing
MW	=	Molecular weight of NOx	=	46 lb/lb-mole
UC	=	Unit Conversion	=	453.6 g/lb
SV	=	Specific Volume	=	(379.5 SCF/lb-mole)

To calculate the E-3 Cycle weighted NOx g/bhp-hr:

NOx g/hp-hr = $\sum(Wt_i * NOx\ g/hr_i) / \sum(Wt\ Factor_i * Hp_i)$

Where:

Wt_i	=	E-3 weighting factor at test mode "i"
NOx g/hr_i	=	Measured NOx grams per hour at test mode "i"
Hp_i	=	Engine horsepower at test mode "i" [6]

7. Reporting

The local air agency that is administering the Carl Moyer Program will submit a report to CARB demonstrating the results of the NOx testing. The report shall include the emissions calculation spreadsheet, the raw emissions test data, and the results of the instrument calibration and accuracy checks.

[5] The moisture fraction of the ambient air can be determined with wet bulb thermometer or sling psychrometer. In lieu of measuring actual moisture content of ambient air, CFR 40, Part 60, Method 19, Section 2.2.1 provides alternate means for estimating ambient air moisture content, including the use of a default factor.

[6] For propulsion engines, horsepower will be based on the engine's propeller power curve at the appropriate E-3 Cycle test RPM. For auxiliary engines, horsepower will be based on the engine's industrial power curve.

Attachment A

Example Instrument Calibration and Interference Response Recordkeeping Forms

Pre-Test Calibration and Checks

Date: ____________ Tester: ______________ Boat Name: ____________

Analyzer: Model # ________ Ser. No. __________ Sampling System # ________

Sensitivity Range: NO: 0 – ____ ppm NO2: 0 – ______ ppm

Sampling System Accuracy Check

Channel	Range	Conc. (ppm)	Analyzer Response (ppm)	Response minus Cal Gas	Error (% of Cal Gas Conc.)	Error Limit % (ppm)	Error (% of Range Conc.)
NO (high)	**Zero**						
	Mid						
	Cal						
NO2	**Zero**						
	Mid						
	Cal						

Sampling System Interference Check

Channel	Gas	Conc. (ppm)	Analyzer Response (ppm)	Response minus Cal Gas	Error (% of Cal Gas Conc.)	Error Limit % (ppm)	Error (% of Range Conc.)
NO (high)	**NO2**						
	NO/ SO2						
NO2	**NO**						
	SO2						

Calibration Summary

NO Calibration: Successful / Unsuccessful Interference Response: OK / Error

NO2 Calibration: Successful / Unsuccessful Interference Response: OK / Error

Post-Test Checks

Date: ______________ Tester: ________________ Boat Name: ______________

Analyzer: Model # ________ Ser. No. ________ Sampling System # _________

Sensor Range: NO: 0 – _____ pm NO2: 0 – ____ ppm

Sampling System Bias Check

Channel	Range	Conc. (ppm)	Analyzer Response (ppm)	Response minus Cal Gas	Error (% of Cal Gas Conc.)	Error Limit % (ppm)	Error (% of Range Conc.)
NO (high)	**Zero**	0					
	Mid						
	Cal						
NO2	**Zero**	0					
	Mid						
	Cal						

Sampling System Interference Check

Channel	Gas	Conc. (ppm)	Analyzer Response (ppm)	Response minus Cal Gas	Error (% of Cal Gas Conc.)	Error Limit % (ppm)	Error (% of Range Conc.)
NO (low)	**NO2**						
	NO/ SO2						
NO (high)	**NO2**						
	NO/ SO2						
NO2	**NO**						
	SO2						

Attachment B

E-3 Test Cycle

Attachment C

Example Propeller Power Curve

Attachment D

Example Emissions Test Recordkeeping Form

Carl Moyer Marine Repower Program
Emissions Test Data Sheet – Main Engine

Test Date: ____________ Test Engineer: ____________________________

Vessel Description

Name: ________________________

Usage: ____

Manufacturer: ____________________ Year: _________ Length: ________Ft. Displ. ____tons

Hull Type: Planing / Semi-planing / Displacement Construction: ________________________

Engine Description

Year/Make: ____________ Model: __________ Total hrs: __________ Hrs since last rebld: ________

Exhaust: wet / dry Turbo: Yes / No Aft. cooler: Yes / No Enh. Aft. cooler: Yes / No

Manu. Max Continuous RPM: __________

Ambient Conditions

Temperature: __________F Wind: kts Sea state:

Test Data

E-3 Cycle Load	E-3 Cycle RPM	Targeted RPM	Test Sample	Actual RPM	NO ppm	NO2 ppm	O2 percent	Speed (kts)
100%	100%		1					
			2					
			3					
			Average					
75%	91%		1					
			2					
			3					
			Average					
50%	80%		1					
			2					
			3					
			Average					
25%	63%		1					
			2					
			3					
			Average					

Comments:

Marine Repower Program
Emissions Test Data Sheet - Auxiliary Engine

Test Date: ______________ Test Engineer: ____________________________

Vessel Description

Name: ____________________________
Usage: ____
Manufacturer: _______________________ Year:________ Length: _________ ft.
Hull type: planing / semi-planing / displacement
Construction: __________________________________ Displacement:_________ tons

Engine Description

Auxiliary engine used for: ____

Make: _________________ Year/Model:_______________ Hours: __________

Exhaust: wet / dry Turbo: Yes / No Aft. cooler: Yes/ No Enh. Aft. cooler: Yes / No

Manu. Max Continuous RPM: ___________

Ambient Conditions

Temperature: ___________F Wind:______kts Humidity[1] ________

Test Data

Estimated Load	Test Sample	Actual RPM	NO ppm	NO2 ppm	O2 percent
	1				
	2				
	3				
	Average:				

Comments:
____
____
____
____

\\nt3\groups\ITG\WP\D-5 Marine Engine Repower\trawler99\Boat Source Testing\[emissionstestdatasheet.xls]aux engine test sheet

1. Humidity is only required if using wet sampling/testing methods.

Attachment E

Example Emission Calculation Spreadsheet